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Real Options in Operations Research: A Review and Synthesis

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Highlights

- Reviews 164 papers from five internationally-renowned journals between 2004-2015.
- Papers employ the Real Options approach to Operations Research settings/problems.
- Catalogues 6 subject themes where the Real Options approach has been most valuable.
- Identifies, per theme, the main modeling approaches, key issues and sub-categories.
- Documents current trends and suggests promising directions for future research.

Real Options in Operations Research: A Review and Synthesis*

Lenos Trigeorgis† Andrianos E. Tsekrekos‡

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Abstract

The Real Options (RO) approach to decision-making has been useful in capturing and valuing the flexibility inherent in many operating decisions that decision makers are faced with. In Operations Research (OR), a field that encompasses a plethora of problem-solving techniques for improving decision-making, we note an observable steady increase in contributions that apply the Real Options approach to model, analyze and evaluate flexible operating alternatives available to decision-makers or to optimize the operational efficiency of decision timing. We review 164 papers that appeared in five internationally-renowned OR journals in the last twelve years, cataloguing the main subject themes and contributions where the Real Options approach has been most valuable to Operations Research. We classify the reviewed papers into six main subject themes, and identify their main characteristics, the modeling approaches used, key issues and sub-categories. We further document current trends and suggest promising opportunities for future research.

Keywords: Finance; Review article; Real Options; Investment under Uncertainty; Operations Research sub-disciplines.

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1. Introduction

'Real Options' describe corporate assets including growth opportunities viewed as options whose value depends on discretionary future investment by the firm (Myers, 1977). These corporate assets include not only tangible real assets acquired by firms through direct investment, such as plant and equipment, but also the successful outcomes of outlays in research and development (R&D), learning outcomes acquired via expenditures in training and advertising, and potential complementarities in product and service markets contingent on initial investment expenditures.

'Real Options' are contingent on *discretionary future* investment in that the magnitude, timing and schedule of investment outlays (e.g. whether lump-sum or in stages) affects the value of firm growth opportunities, such that their active management by decision-makers can be value-enhancing for the firm. Following Myers' footsteps, many researchers—exploiting concurrent developments in financial option pricing techniques—further refined and developed option-based approaches to firm and investment valuation.[4] The work of Brennan and Schwartz (1985), McDonald and Siegel (1985,1986), Trigeorgis (1986), Pindyck (1988) and Dixit (1989), rooted in two decades of advances in option pricing theory, helped establish the foundation of what is nowadays referred to as the 'Real Options' (henceforth RO) approach to decision-making. This foundation is reviewed, synthesized and further developed by the highly-cited work of Dixit and Pindyck (1994) and Trigeorgis (1993a, 1996).

As the field of Operations Research (henceforth OR) inherently relies on various problem-solving techniques for improving managerial decision-making under conditions of uncertainty, it was natural for OR scholars to adopt and seek to extend the RO approach (as early as the 1990s). Applications ranged from the valuation of flexibility inherent in production systems (see, e.g. Triantis and Hodder, 1990), the implementation of supply-chain collaborations and manufacturing joint ventures (e.g. Kogut, 1991), capital budgeting evaluation of R&D investment projects (Pennings and Lint, 1997), and the valuation of natural resource reserves (Smith and McCardle, 1998), to name a few. More recently, we witness a steady increase in OR contributions that apply the RO approach to model, analyze and evaluate the numerous flexible alternatives that are available to decision-makers and to optimize the efficiency of managerial decision timing.

The main purpose of this article is to provide a contemporary review of influential articles in OR journals that employ the RO approach during the last twelve years. Our main objectives are (1) to identify recent OR academic papers that employ RO concepts and modeling, and (2) establish the main subject themes (OR sub-topics) where the RO approach has been most valuable to the OR scholarly community. By reviewing and cataloguing the research contributions that we identify within each subject theme/topic, we are able to sketch their common characteristics and modeling similarities as well as propose promising paths for future research. We thus compile, manage, structure and classify a wide-ranging body of OR research within the canopy of RO.

[4] Articles by Samuelson (1965), Black and Scholes (1973), Merton (1973), Cox and Ross (1976), Cox, Ross and Rubinstein (1979), Harrison and Kreps (1979), Harrison and Pliska (1981, 1983), among others, have provided important developments in financial economics and financial option pricing.

We focus our review on papers that employ the RO approach and which appeared in five select internationally-renowned OR journals in the last twelve years. Specifically, we identify 164 RO-related papers published between 2004 and 2015 in the following OR journals: *Operations Research* (hereafter OR), *Management Science* (MS), *European Journal of Operational Research* (EJOR), *Annals of Operations Research* (ANOR), and *International Journal of Production Economics* (IJPE).[5] We propose a categorization of these 164 contributions into six main subject themes (OR sub-topics). We track the evolution of the six subject themes over time during our sample period and examine which specific themes of the RO related contributions are more covered or prevalent in these OR journals.

Alongside cataloguing the content of these 164 articles during the recent 12-year coverage period in our review (and the Supplementary material), we cite some influential work published before the starting year of our review (2004), as they help provide perspective and depth for the other reviewed articles (these are listed separately under supplementary references). Beyond our comprehensive survey and convenient summary of the covered articles, this article includes a classification with six appropriate topic categories (subject themes), the single-firm versus multi-agent setting (or RO games), a modeling synthesis (in Supplementary Appendix) and directions for further research.

The article is organized as follows: Section 2 describes the approach we followed in conducting this review and presents summary statistics on the identified OR papers that employ RO. Section 3 provides a survey of the 164 papers identified in the literature, describes the six main subject themes/topics where the RO approach has been fruitfully employed in OR, discusses their evolution over time, and the common characteristics shared within each subject theme. Section 4 concludes and suggests paths for future research. The Supplementary Appendix synthesizes the basic aspects and underlying formulations of typical RO models that are employed in the OR literature.

2. Review method and descriptive statistics

Our review approach followed three steps:

(a) Identify important recent contributions in the OR literature that employ RO concepts and modeling,
(b) Review identified contributions to ascertain the main themes and topics where the RO approach has been most applicable and valuable to OR, and
(c) Survey the research contributions within each identified main theme to ascertain their common characteristics and opportunities for future work.

In step (a), our approach was to focus on a well-specified time frame and journal universe. We restricted our review to the 2004-2015 time period and to five select internationally-renowned OR journals.

We focus on the last twelve years so as to keep the review contemporary, while maintaining a time length long enough to identify recent trends in the relevant literature. Our starting year (2004) marks a decade since the influential work of Dixit and Pindyck (1994) and Trigeorgis (1993, 1996) that firmly established the RO literature. During this

[5] Although several other internationally-renowned OR journals also feature research papers following the RO approach and could be included in this review, we hope that the main themes and typical problems where the RO approach has been valuable to Operations Research are sufficiently covered by just reviewing the five selected journals.

first decade, the contingent claims approach to the flexibility inherent in managerial decisions has been well-established as a modeling and valuation method, and our present research review is primarily interested in following on and reviewing its extended impact in OR after this first decade. We restrict the review to only these five select but influential journals in order to keep the review length manageable but with high impact content.

Operationally, we conducted step (a) as follows. For each journal within the 2004-2015 period, we performed an advanced search using the following union of keywords and conditions (i.e., all of them joined with an 'OR' Boolean operator):

- '*real options*' anywhere in the text, OR
- '*investment under uncertainty*' anywhere in the text, OR
- '*options*' in the paper's title, abstract or keywords, OR
- '*uncertainty*' in the paper's title, abstract or keywords.

The search was conducted between May and September 2015, was repeated in December 2015 for any new related published papers, and includes any accepted manuscripts not yet assigned to the journals' issues. The aforementioned search yielded results ranging from the hundreds (ANOR, IJPE, MS, OR) to the thousands (EJOR) within our time period (mainly due to the last two search criteria).[6] We manually checked all search results to finalize the identification of relevant papers reviewed in this study. We opted to be as exhaustive as possible, in that we also included (a) other literature review articles which might have a different subject focus but which discuss RO as an approach employed by researchers in that subfield (e.g., Julka et al., 2007), and (b) short papers that, e.g. juxtapose RO with other optimization approaches in the literature (e.g., Wallace, 2010).

Our keyword and manual search yielded a total of 164 papers that have appeared in the selected OR journals between 2004 and 2015. These are distributed as follows: 70 papers (43%) appeared in EJOR, 34 papers (21%) in IJPE, 33 papers (20%) in MS, 18 papers (11%) in ANOR, and 9 papers (5%) in OR. Related publications in EJOR are almost twice as many as those in IJPE or MS; this is natural, however, as EJOR published roughly as many papers as all other selected journals combined during the examined period.[7] In EJOR, the 70 identified contributions that employ RO concepts and modeling represent 1% of the journal's total output over our examined twelve-year period. Equally, in IJPE and ANOR they represent roughly 1% of their total output, while in MS and OR the representation is 1.8% and 0.8%, respectively.

To help better appreciate the total related-research output by the five journals during the 2004-2015 period, Figure 1 plots the number of RO related research papers published by each journal per year during the recent 12-year period. In Panel A, which shows the total number of published research papers per year, the RO related research volume has

[6] These last two broad search criteria contribute about 10%-15% to the final list of identified papers.
[7] EJOR published 7,552 papers between 2004 and 2015, an average of about 630 papers per year. This is almost the entire output of IJPE (3,497 papers), ANOR (1,947), MS (1,789) and OR (1,179) combined. The published paper numbers we report exclude withdrawn and retracted papers, book reviews, calls for papers, acknowledgements to reviewers, and letters from and to the editors (but include errata, corrigenda, technical notes, replies, and introductory articles to special issues).

increased by more than 50% from the first six-year sub-period (64 articles in 2004-2009) to the second sub-period (100 articles in 2010-2015). There is a clear upward trend in the number of published RO-related papers from 2007 onwards.[8] Panel B of Figure 1 shows the time evolution of the volume of each journal's publications over the 2004-2015 period. There is a steady increase in the number of published RO-related papers by EJOR and IJPE, while the trends in OR and MS seem rather steady or decreasing.[9]

[Insert Figure 1 about here.]

Once the recent contributions in OR that employ RO concepts and modeling have been identified, in step (b) we review the identified papers in order to establish their main themes, namely the main OR sub-categories and problems where the RO approach has been typically employed. As an overview, we identify the following six themes (OR sub-categories) in which the use of the RO approach has been more prevalent:

A. *Uncertainty and Investment* (31 papers, 18.9% of reviewed papers)
   In typical investment timing problems, uncertainty—and irreversibility of capital investment—negatively affect investment rates as decision-makers recognize the 'option value of waiting' before sinking a fixed investment cost. A steady number of papers that follow the RO approach, highlighting aspects of the uncertainty-investment relationship, appear regularly in OR journals.
B. *R&D, Innovation and Technology* (30 papers, 18.3% of reviewed papers)
   Innovative breakthroughs (technological, pharmaceutical, etc.) accomplished via intensive research and development efforts with uncertain outcome, followed by numerous stages of testing and approval before they are marketed, represent a natural setting for applying the RO approach. From early on, OR scholars employed RO in R&D valuation, patent races and new technology adoption.
C. *Production and Manufacturing* (37 papers, 22.6% of reviewed papers)
   In the presence of stochastic output demand or input price uncertainty, flexible production systems that allow production schedules and allocation of resources to be adaptive to new information and to unexpected changes in key underlying variables have been used to enhance the robustness and efficiency of operations. Option-based methods proved well-suited for modeling and highlighting such flexible production systems. In a global economic environment, the decision whether to partially or completely outsource manufacturing operations (and for how long) also proved a valuable option to decision-makers.
D. *Supply Chain and Logistics* (29 papers, 17.7% of reviewed papers)

[8] Years 2006 and 2009 seem the 'least productive' (with 7 published articles each year), while years 2010 and 2015 are the 'most productive' (with 21 published articles per year) during this period.
[9] The 12 (respectively 7 and 5) RO-related papers that appeared in EJOR (respectively IJPE and ANOR) in 2012 (respectively 2012 and 2015) represent 2% of the journal's total output that year. This rises to 4.2% for MS and OR in their respective 'most active' years (2006 and 2004 respectively).

Bilateral options that suppliers and manufacturers grant each other as part of the agreed terms of a supply chain configuration have been thoroughly examined using RO methods in several OR studies. Specifically, the 'option to change suppliers' or the extent to which firms in a supply chain collaborate or compete for better agreement terms has been fruitfully modeled as an 'option game'.

E. *Energy, Natural Resources and Environment* (22 papers, 13.4% of papers)
Investments in infrastructure (energy, telecommunications, etc.), as well as the use of land and the management of natural resources, have been regular topics of applied research where RO has proven helpful in OR since the field's inception.

F. *Valuation Models and Other Topics* (15 papers, 9.1% of reviewed papers)
A variety of other topics and applications that are not easily classified in the previous themes, ranging from e.g. the 'option' to move from waged work into self-employment (Folta et al., 2010), to experimental evidence that vagueness affects the exercise of investment options (Du and Budescu, 2005), have also appeared in select OR journals, and are categorized as a separate heterogeneous theme. In this theme, we also include papers that prescribe valuation and numerical refinements for the application of RO methods to practical OR problems.

It should be noted that the proposed thematic categories may overlap in that some papers could be attributed to more than one category. Excluding the last theme (F), there is a fairly even distribution of RO-related contributions across the first five thematic categories.[10] Figure 2 plots the number of reviewed papers per identified theme (A-F), aggregated over two consecutive six-year periods (2004-2009 and 2010-2015). There is a discernible and significant increase of related research in most themes. The output of RO-related papers dealing with themes of *Uncertainty and Investment*, *Supply Chain and Logistics*, and *Production and Manufacturing* nearly doubled in the last six years. RO papers concerned with *Energy, Natural Resources and the Environment* were up 75% (from 8 to 14) in the most recent six-year period. Only the applications of RO analysis to *R&D, Innovation and Technology* were more popular in the early sub-period.

[Insert Figure 2 about here.]

We next examine whether any of the six identified themes (OR sub-topics) tend to appear consistently in any specific journal. Table 1 reports the number (with % in parentheses) of RO papers published in each of the five journals, per identified theme. Figure 3 provides a graphical illustration. EJOR featured the majority of RO papers on *Uncertainty and Investment* (theme A) and *Energy, Natural Resources and Environment* (theme E) during the examined period, while IJPE was preferred for *Supply Chain and Logistics* (theme D). EJOR and IJPE also enjoyed the 'lion share' of contributions on *Production and Manufacturing* (theme C), while MS featured most papers on *R&D, Innovation and Technology* (theme B). ANOR has focused more on *Energy, Resources and Environment* (theme E), while OR was more receptive on *Supply Chain and*

[10] Theme B has perhaps been more fully explored in OR journals than elsewhere till now.

Logistics (theme D). The six themes we identify are discussed in more detail in Section 3 of the paper, which examines the similarities and common modeling characteristics within each theme. As an initial indication, Table 2 provides an alphabetical list of the 164 papers along with some of their key aspects.

[Insert Table 1, Table 2 and Figure 3 about here.]

Table 2 categorizes the reviewed papers across several dimensions: the first dimension refers to models developed for a *single-firm* (or single-agent) *setting* (Panel A, 111 papers) vs. *multi-agent settings* or *Real Options games* (Panel B, 53 papers). By *single-firm setting*, we refer to models where one agent (i.e., a firm, supplier, producer etc.), in isolation, is interested in optimally managing the flexibility inherent in a decision (over timing or across competing alternatives). In *multi-agent settings* and *Real Options games* we categorize models where one agent's options and available alternatives are affected by the actions and decisions of other agents, such as competitors.

The second dimension distinguishes between *general-context* models (Panels A.1 and B.1, 77 and 42 papers, respectively) and *context-specific* models (Panels A.2 and B.2, 34 and 11 papers respectively). Under the *context-specific* category we classify case studies (e.g., Wong et al., 2011) as well as models motivated by industry-specific problems (e.g., wind power generation in Muñoz et al., 2011; airline alliances in Graf and Kimms, 2011, etc.). This is not to imply that the findings or implications of these models do not apply or are not generalizable to other contexts, but rather that these models are derived with specific industries or particular problems in mind.

Under column four in Table 2 (General Theme/Topic), we also report which of the six main subject themes of RO analysis in OR that we identified through step (b) applies, as well as a number of other dimensions that allow sub-categorization. The *Theory (New/Refine)* dimension refers to whether the article proposes a new theoretical framework or it provides a refinement of existing theoretical approaches. If a reviewed paper is empirical, or includes an applied section, it is marked accordingly (with a ✓) on the *Applied or Empirical* dimension. The *Information* dimension refers to whether all agents in the paper's setting possess complete or incomplete information. Finally, under Authors' keywords, we list select keywords the authors have used for their paper.[11] A more complete description of each reviewed paper is given in the last columns of Tables S1-S6 in the paper's supplementary material (under Key Features).

The six main subject themes we identified, along with the above distinctive dimensions that allow a sub-categorization of contributions within each theme, are discussed in more detail in Section 3, which constitutes our implementation of step (c) above. The Appendix provides a synthesis of general RO models and OR techniques used in the RO literature for the more technically-inclined reader (some of which are referenced later on with particular citations given).

3. Recurrent themes and applications of real options in operations research

[11] Keywords 'real options' and 'uncertainty' that are recurring in almost all papers, have been omitted from this final column entries.

3.1 Theme A: Uncertainty & Investment

The contributions categorized under '*Uncertainty & Investment*' (Theme A) are summarized in chronological order in Table S1 of the supplement. A brief synopsis highlighting the key features of each paper appears in the last column of Table S1. Common investment timing problems where uncertainty and irreversibility of investment give rise to an 'option value of waiting' are further categorized into (a) single–firm investment problems, (b) real options games, and (c) principal-agent incentives and contracting.

3.1.1 Single–firm investment problems

The major distinction made here is between *complete* and *incomplete information* settings, depending on whether the decision-maker (a single firm in isolation) has perfect or imperfect information regarding the crucial parameters that determine the attractiveness of the investment project.

Complete information setting: In this setting, prior research has investigated how uncertainty and added complexities or contingencies affect investment timing strategies. The complete information setting with uncertainty typically results in two regions (wait/invest) separated by a critical threshold for immediate investment that is much higher than that given by the traditional deterministic OR models. There are exceptions which alter or reduce these thresholds, as first noted by Tourinho (1979), such as a holding cost or an increasing investment cost. A different kind of exception arising from extra complexities and contingencies is noted by Battauz et al. (2015): under specific conditions (predominantly an 'essentially negative' interest rate), finite-maturity American-style options exhibit a double-continuation region, where immediate exercise (investing) is optimally postponed not only when the option is not sufficiently in the money but also when it is too deep in the money.[12] Exploiting the homogeneity of this investment setting, the investment option problem is formulated as a put (real) option on the cost-to-value ratio ($X_t = I_t/V_t$, see McDonald and Siegel, 1985); for the finite-maturity case, the authors argue that an 'endogenous' negative interest rate might arise in case of a very profitable investment project (i.e. $\mu_V > r$), leading to a nonstandard double-continuation region when the investment cost is expected to increase markedly more (i.e. for $\mu_I > \mu_V$). Such a case of an extremely profitable investment project with $\mu_V > r$ is 'assumed away' in a perpetual real options setting (as it leads to non-convergence and explosive present values), yet it can be relevant for most real-life projects involving finite investment horizons.

[12] The implications are explored via an example corresponding to $K = 1,\ L = 1, r_k \equiv r$ in the general modeling of Supplementary Appendix (Section A.1), and a two-dimensional ($M = 2$) variant of equation (A1), with $m_1\big(t, Y_1(t)\big) = \mu_1 Y_1(t) = \mu_V V_t$ and $s_1\big(t, Y_1(t)\big) = \sigma_1 Y_1(t) = \sigma_V V_t$ (the drift and diffusion of a project's gross present value) and $m_2\big(t, Y_2(t)\big) = \mu_2 Y_2(t) = \mu_I I_t$ and $s_2\big(t, Y_2(t)\big) = \sigma_2 Y_2(t) = \sigma_I I_t$ (the drift and diffusion of the project's investment cost).

Kort et al. (2010) examine the trade-off between completing an investment project in one stage at a chosen time or in stages that can be completed at optimally selected points in time.[13] This trade-off in Kort et al. (2010) is due to economies of scale, as completing the project in one stage costs less but proceeding stepwise allows flexibility of selecting the investment timing for each of the two stages. They find that high uncertainty favors the lumpy (one-stage) investment commitment relative to the stepwise investment, implying that the notion of uncertainty favoring flexibility is not applicable to such simple 'splits' of investment opportunities in stages. Alexander et al. (2012) argue in favor of using a (one-dimensional) arithmetic Brownian motion (as an alternative to the usually-employed geometric Brownian motion, hereafter gBm) for modeling the underlying value of an investment project. Such a stochastic process allowing for negative path realizations as a project becomes unprofitable, they argue, might be more appropriate when investment projects are treated as incremental ventures financed from the same pool of limited resources managed by a single decision-maker.

Dias and Shackleton (2011) instead focus on interest rate uncertainty, assuming it is the instantaneous rate of interest that follows a stochastic process rather than the investment's revenues or costs (which are here assumed constant). They specifically assume that the instantaneous interest rate follows the process in (A1) of the Supplementary Appendix with $M = 1$, $m\left(t, Y_j(t)\right) = \eta(\bar{Y} - Y(t))$ and $s\left(t, Y_j(t)\right) = \sigma\sqrt{Y(t)}$ (the CIR square-root, mean-reverting process of Cox et al., 1985), and they establish the conditions for calculating the optimal interest rate entry and exit thresholds. They conclude that firms switch to durable assets (via investment) from cash ("an immediate asset") for sufficiently low interest rates. Similarly, in Chronopoulos et al. (2011) a risk-averse decision-maker with an infinite planning horizon can switch costlessly between (riskless) cash and a risky asset (investment) involving positive operating costs requiring an unrecoverable investment cost when initiated. Accounting for risk aversion in an 'incomplete markets' setting, the authors employ a utility-based framework focusing on how the flexibility of suspending and resuming the investment project alters the standard result that risk aversion suppresses real option values and lowers propensity to invest. For a variety of utility functions, they establish that such suspension and resumption options partly mitigate the effect of risk aversion by increasing the likelihood of investment in the risky project, and that the operating flexibility provided by such options is more valuable in more volatile environments and for more risk averse agents. Sbuelz and Caliari (2012) also deal with the effect of risk aversion on the optimal timing policy in a typical complete-information single-firm investment problem. In their setting, an unlevered firm (whose cash flows from assets in place exhibits volatility that depends on an exogenous economy-wide state-pricing process) can opt to scale-up its cash flows by a constant multiplier $\theta > 1$ by incurring an irreversible investment cost at any time. Focusing on the joint impact of risk aversion and of state-dependent cash flow risk on firm value and on optimal growth option exercise, the authors show that the growth option on a firm's assets in place increases the convexity of the firm's stock price with respect to its cash flow level such that expected firm equity returns are enlarged.

[13] In the notation of the general model of Supplementary Appendix (Section A.1), their setting corresponds to $K = 1$, $L = 2$, $\pi_{h,l}^{k}\left(Y(t); \varphi_{h,l}^{k}\right) = Y(t)\sum_h R_h$, with R_h, $h \leq l$ constants, and assumes that the stochastic part of the project's payoff follows a one-dimensional ($M = 1$) geometric Brownian motion (gBm) .

Related contributions by Hackbarth et al. (2014), Shibata and Nishihara (2015) and Morellec et al. (2015) are concerned with the joint determination of investment and financing decisions when the firm finances its investment project with equity and debt (private or public or both). Shibata and Nishihara (2015) deal with the case that the firm can finance its investment either by public/market debt (a perpetual bond) or via a bank loan with the only difference between the two being the bankruptcy procedure: the firm is liquidated (or respectively, it survives and debt is renegotiated) under market (respectively bank) debt financing. They focus on how the interaction between financing decisions and investment strategies is affected by debt issuance constraints, assuming that only a maximum fraction q of investment cost I can be raised by debt (public or private). The authors establish that firms facing less restrictive debt issuance constraints (larger and more mature firms) are more likely to issue market rather than bank debt, showing that debt issuance constraints do not have a monotonic effect on optimal investment thresholds. In a similar setting, Morellec et al. (2015) assume an initially 'all-equity financed' firm that can scale-up by a constant $\theta > 1$ its cash flows from operations (which follow a gBm) by incurring an unrecoverable investment cost I, that can be financed partly or wholly by market or private debt. Market debt carries constant issuance costs, while private debt involves search costs and negotiation such that private debtors can extract part of the investment surplus via Nash bargaining. Abstracting from debt issuance constraints, they assume that upon default only private debt can be renegotiated (swapped with equity) via bargaining. Jointly determining the investment-financing-default policy, they conclude that *"firms with more growth options, with higher bargaining power in default, operating in more competitive product markets, or facing lower credit supply are more likely to issue bonds"* (p.18). The authors also empirically test their model predictions on a sample of U.S. firms over the 1988-2007 period, finding evidence supporting their hypotheses. By contrast, in Hackbarth et al. (2014) only one form of debt financing (a perpetual loan) is available to the decision-maker. The manager jointly determines the investment-financing-default policy for a project that can be implemented under two alternative organizational forms: in the *"integrated"* form, the new project is implemented as part of an existing firm with a predetermined capital structure, while in the *"non-integrated"* form, the new investment is undertaken under a new separate corporate entity that can optimally decide the debt-to-equity mix. The authors conclude that "integration" preserves the value of assets-in-place, whereas "non-integration" favors real option value and maximizes financial flexibility.

Chiu et al. (2015) examine stock loans, where a borrower uses shares of stock as collateral for a loan and retains the right to regain the stock by paying a time-varying price within a finite horizon. They consider regime switching, and propose that management of perishable services (like recallable air tickets) and the launching of fashionable products (e.g. movie merchandise) be treated analogous to finite-maturity stock loans. Arkin and Slastnikov (2007) consider investment timing and depreciation policy, and specifically whether a government should allow a higher depreciation rate (motivating earlier investment) along with higher revenue tax rates. They examine the parameter domain that combines *both* higher tax revenue *and* investment incentives and show that higher uncertainty shrinks this domain restricting the ability of government to offer investment incentives through depreciation policy. Other interesting applications or refinements of the *complete-information* setting include the effect of time lags on investment timing (Kim et al., 2008), operational hedging strategies of global firms facing fluctuating exchange rates (Dong et al., 2014), and optimal advertising efforts when sales response is uncertain (Du et al., 2007).

Incomplete information setting: Thijssen, Huisman and Kort (2004) modify single-firm decision rules to account for imperfect information. In their model, imperfect signals about the attractiveness of an investment project are received 'costlessly' at random times, leading to Bayesian updating of managerial beliefs regarding the investment opportunity. The signal arrival times and type ('good' or 'bad') are modeled via two correlated binomial processes. By delaying investment and waiting for more signals to arrive, the firm can predict with better accuracy whether the investment project is indeed profitable or not. The authors derive the optimal decision rule in terms of a critical level (threshold) for the belief that the project is good, which must be exceeded for the investment to be optimal, and show that this threshold level depends on the reliability of the signals, their number and the decision maker's discount rate.

Harisson and Sunar (2015) similarly apply Bayesian updating in a setting where the firm can reduce project value uncertainty by employing any of several available learning modes, each one involving a different cost. They show that the firm will choose to apply only the learning modes that reside on an efficient frontier (in terms of *"cost rate vs. signal quality"*) and derive the optimal belief thresholds (as in Thijssen et al., 2004) that suggest immediate project abandonment or immediate investment.

Shibata (2008) considers a firm that accumulates cash flows by undertaking an *"initial activity"* (e.g. marketing, R&D, etc.) which is assumed costless to initiate or terminate. These accumulated cash flows act as noisy signals of the true but unobserved cash flow process (assumed to be Ornstein-Uhlenbeck in this setting). The realizations of the accumulated cash flows are 'Kalman-filtered' by the decision-maker in an effort to infer the true level of project cash flows.[14] Shibata (2008) obtains numerical estimates of the thresholds for initiating and terminating this information-generating *activity*, and concludes that incomplete information raises investment inertia (the negative effect of uncertainty on investment).

3.1.2 Multi–agent problems and option games

Most refinements of the standard real option game involving multiple agents assume *complete information*.[15] Haanappel and Smit (2007) analyze the return dynamics of strategic growth options when competing firms have investment-timing differences, while Ko et al. (2011) apply the standard option game setting to analyze competition between two venture capitalists that contemplate investing in the same start-up firm. Kong and Kwok (2007) and Chronopoulos et al. (2014) extend the setting described in Section A.2 of the Supplementary Appendix to account for asymmetric competitors and risk aversion, respectively. Kong and Kwok (2007) allow duopolistic competitors to differ both in the investment cost that they need to incur to enter the market and in the revenue flows obtained when operating in the market. These asymmetries allow a fuller characterization of the pre-emptive and simultaneous equilibria that might arise in the standard real option game. Chronopoulos et al. (2014) account for risk aversion

[14] See e.g. Øksendal (2003) for the Kalman filtering problem.

[15] A notable exception is Nishihara and Fukushima (2008) who examine a duopolistic setting involving a small start-up that pioneers a new market and a large firm that eventually takes over the market from the start-up. The authors evaluate the start-up's loss due to its incomplete information about the large firm and derive the conditions under which the start-up should use more information about the large firm.

assuming that the preferences of the two competing firms are described by a utility function that exhibits constant relative risk aversion (CRRA). They show that risk aversion causes both the leader and the follower to delay their investment entry, in both pre-emptive and non-pre-emptive settings. Moreover, in a pre-emptive setting, higher uncertainty reduces the relative loss in value incurred by the leading firm (temporary monopolist) when the follower enters the market; however, in a non-pre-emptive setting the impact of uncertainty is ambiguous as it depends on the magnitude of post-entry duopolistic market shares.

Real option games with agents co-operating instead of competing for a single market or investment are analyzed by Lukas et al. (2012) and Banerjee et al. (2014). Banerjee et al. (2014) examine timing problems where two or more firms create a surplus by *jointly* exercising an option. Such situations, where a real option can only be exercised if the parties involved agree on the exercise timing and on the rule of how the proceeds will be divided, are common in joint venture agreements, R&D alliances, collaborative supply chains, and mergers and acquisitions (M&As). In their model, the two parties that share an irreversible investment cost (I_i and I_j) must decide via Nash bargaining how to divide the proceeds (with fractions $\gamma_i + \gamma_j = 1$) and any bilateral direct payments required for additional compensation before the investment is implemented. Their findings suggest that allowing one of the parties to select the investment timing is socially efficient if it precedes the bargaining on the terms of sharing. In contrast, if the sequence is reversed with the sharing rule agreed before the investment exercise timing decision is made, socially optimal timing can only be attained if there is a cash side-payment in the division of the surplus.

In a related setting examining contingent earnouts in M&As using an option game approach, the timing of the takeover is decided first, and only then the target firm chooses its level of post-takeover cooperation that affects the level of synergies realized post-deal (Lukas et al., 2012). The authors show that higher uncertainty leads to a higher earnout ratio and the same is observed as the earnout period is prolonged.

3.1.3 Principal/agent settings: Incentives and contracting

A large number of multi-agent real options contributions focus on the incentives of principals and agents in a firm-investment context, their interaction under incomplete information and how information is revealed by their actions (or lack thereof). Mittendorf (2004) finds that information revelation and incentive spillovers can significantly affect the exercise and valuation of a real investment option. In a discrete model, the (risk-neutral) principal designs a compensation contract to motivate the (risk-neutral) agent and decides whether or not to expand the scale of operations based on information (observed privately) about the profitability of the expansion. Although a standard reason for delaying expansion is absent from the model (no new information arrives), the author shows that the option to delay expansion can still be valuable as it allows the principal to prolong her information advantage over the agent.

In a related paper, Delaney and Thijssen (2015) investigate the effect of corporate voluntary disclosure on the timing of a firm's investment decisions when again the manager of the firm receives signals at random times which help partly resolve the uncertainty of investment profitability.[16] However, unlike Mittendorf (2004), where investment option exercise or its delay serve as the sole signals regarding the profitability of the investment, here the manager has the extra option to disclose the investment return to 'outsiders' with the aim of maximizing her monetary payoff. For the disclosure option to have value, the manager's remuneration is linked to the firm's stock price: the manager's disclosure of investment returns is unexpected information to 'outsiders' who respond by altering their demand for the firm's shares. The authors show that since voluntary disclosure affects compensation (through its effect on the firm stock price), the manager is motivated to invest at a sub-optimal time compared to the first-best investment strategy that a manager with remuneration independent of the firm's stock price would have chosen.

Shibata and Nishihara (2011) deal with agency conflicts between principals (owners) and agents (managers) in an investment timing context with a focus on managerial effort and how optimal contracting might align management efforts and incentives with firm value maximization.[17,18] The manager has an incentive to untruthfully report the 'high' investment cost regardless of true realization, unless an incentive scheme is offered by the owner. The authors show that, in equilibrium, this asymmetry of information causes inefficiency in investment timing selection but leads to higher efficiency in management effort compared to the full-information setting.

3.2 Theme B: R&D, Innovation and Technology

Table S2 (Supplementary material) summarizes, in chronological order, the reviewed contributions under this theme. Investments in new technologies and investments that depend on intensive R&D efforts with uncertain outcome presented a natural setting for applying the RO approach early on. The optimal implementation of such projects in stages, their interdependencies with other projects in the firm's R&D pipeline and their active management through information-gathering, learning-by-doing and corrective action midstream such as changing capacity over the product life cycle (e.g. see Bollen, 1999) have been important aspects addressed by the RO approach. Several prominent subthemes are discussed at more length next.

3.2.1 Sources of risk in R&D projects

In R&D, decision-makers typically face numerous uncertainties, many of which are not related to the market or systematic risks associated with the expected cash flow payoff of the completed, commercialized R&D product. Huchzermeier and Loch (2001), before the coverage period for this review, have identified five common sources of

[16] The irregular, random signals are modeled similarly to Thijssen et al. (2004).
[17] Pfeiffer and Schneider (2007) provide a similar treatment in an R&D context.
[18] In their model, investment value follows a $M = 1$ gBm version of equation (A1) in Supplementary Appendix, observable by both the agent and the principal; there are two ($K = 2, k \in \{1,2\}$) possible values for the investment cost, $I_2 > I_1$, management effort affects the likelihood of either I_1 or I_2 occurring and only the manager observes the realized value of the investment cost.

uncertainty in R&D projects, namely uncertainty in (a) market cash-flow payoffs, (b) project budgets, (c) product performance, (d) market requirements, and (e) project schedule. The authors examined how these uncertainties influence the value of managerial flexibility. In their discrete-time model involving L stages to R&D completion and market launch with three available options at each stage ('abandon', 'continue', 'improve', in ascending order of cost), they showed that higher uncertainty in product performance, market requirements and schedule adherence may actually *reduce* real option values. Their intuition is related to the timing of *uncertainty resolution*: managerial flexibility is value-enhancing in the face of high uncertainty only if the latter is resolved *before* revenues or costs occur. In contrast, they find that if operational uncertainty (sources b-d above) is resolved *"*after decisions are made, or if it reduces the probability that flexibility is useful, more variability reduces the ability to respond, and thus diminishes the option value of flexibility*"* (Huchzermeier and Loch, 2001, p. 86). Related subsequent papers covered in this review attempted generalizations of their setting (Santiago and Vakili, 2005), with refinements focusing on the effects of the competitive market environment and the degree of innovation (Kettunen et al., 2015), or methodological proposals directed to R&D managers (Wang and Yang, 2012).

Against such sources of uncertainty, R&D managers have attempted to enhance the value of their innovation efforts by adding new features, improving quality or learning before committing to the next stage of development. Koussis et al. (2007) model such efforts as optional, costly and interacting control actions which are value-enhancing in expectation but with uncertain outcome. They show that such controls introduce path-dependency in the valuation of R&D projects and that staged commitment (flexibility) is preferred if learning effects are present. Wu et al. (2009) and Pendharkar (2010) discuss how interdependencies across R&D stages can be treated operationally in lattice-based valuation algorithms or via multistage stochastic integer programming. Context-specific contributions in R&D and technology and case studies on specific industries and technologies are presented in d'Halluin et al. (2007) in the context of wireless network investment in the cellular phone service industry, Khansa and Liginlal (2009) in information security, Pennings and Sereno (2011) in pharmaceutical R&D, Dimakopoulou et al. (2014) on IT investments in the supply chain, and Morgan and Ngwenyama (2015) on enterprise software upgrades.

In empirical work, Dewan et al. (2007) develop proxy measures of information technology (IT) risk to better understand the risk-return profile of IT investments. Using firm-level IT stock data on a sample of Fortune 1000 firms, the authors propose a way to measure IT risk at the firm level, establish that the returns to IT investment are largely explained by the risk premia associated with such investment and offer insights into the value derived from a RO approach to IT investments.

Liu and Wong (2011) use patent and R&D-related proxies for intellectual capital to empirically test related RO predictions on corporate financing decisions: although intellectual capital has low liquidation value, thus limiting debt capacity, it can enhance it through its positive impact on earnings. The authors report evidence of a positive relation between intellectual capital and leverage, with the biotechnology sector exhibiting the strongest relation in their sample.

3.2.2 R&D project pipelines and innovation commercialization

Firms typically nurture entire portfolios of concurrent R&D projects which share resources and hence are not independent. This leads to a form of "vertical" interdependency among projects at different stages in a firm's R&D pipeline. Chan et al. (2007) suggest that firms actually manage their R&D pipelines in a strategic manner by varying their project selection thresholds or by changing the composition of their pipelines through acquiring and selling projects in technology markets. Using dynamic programming, they establish that the (option exercise) thresholds for advancing (buying or selling) R&D projects are state-dependent. These results imply firms may advance internal projects—even negative expected value ones—to avoid incurring adjustment or transaction costs, affecting firm preferences for project risk. Interesting analyses of innovative R&D pipelines or portfolios in the context of the pharmaceutical industry are given in Zapata and Reklaitis (2010) and Nigro et al. (2014).

Ziedonis (2007), Cassiman and Ueda (2006) and Kamrad et al. (2005) deal with various aspects of the commercialization of successful R&D efforts. Ziedonis (2007) offers an interesting empirical investigation of firms acquiring options to commercialize innovations from the University of California over the 1979-1998 period. This unique dataset allows observation of all firms with an expressed interest in licensing a particular invention, as well as of all licensing steps in the final transaction with the licensee. Consistent with RO theory, Ziedonis (2007) finds that firms are more likely to acquire options on innovations that are exposed to higher technological uncertainty. Firms often exploit the license option period to learn more about the innovation, which may reduce incentives to subsequently actually exercise the option (especially for firms better able to assimilate the innovation).

Examining innovation commercialization from the innovator's perspective, Cassiman and Ueda (2006) consider a model where an innovation can be marketed by the established firm itself, pursued by a new firm start-up (as an external venture) or not commercialized at all. The incumbent firm has limited commercialization capacity, giving rise to an option value of waiting, while new start-up ventures can emerge when this option value is high or innovations are frequently generated. They find that established firms will commercialize innovations that exhibit a high degree of cannibalization with existing operations and fit with existing firm resources.

At an aggregate level, Kamrad et al. (2005) examine an innovator's optimal policy adjustments in advertising or pricing over a set time horizon when the population of potential innovation users moves from (innovation) unaware to the adopter stage via purchasing. This is triggered by factors such as advertising, pricing, word-of-mouth and sales promotion. In a slightly related setting, Chance et al. (2008) evaluate (European-style) real options on movie box office cumulative revenues (movies are short-lived innovations as the authors argue), where cumulative adopters (movie-goers) are partly dependent on previous-period adopters.

3.2.3 New technology adoption and patent/innovation races

As the results of R&D efforts might be marketed at an uncertain time, potential end users face the dilemma of investing now in existing technology (and potentially upgrading later) or waiting to adopt a new technological innovation. Bobtcheff and Villeneuve (2010) consider this dilemma among two mutually-exclusive technologies subject to different uncertainty and characterize the rational regions of investment in the two alternatives. Such dilemmas can be aggravated, however, when competitors can elicit an advantage by operating with the more efficient technology. Huisman and Kort (2001) show that potential invention of a more efficient technology raises the value of waiting to invest in the existing one, but at the same time the presence of competitors may induce the firm not to wait for the new innovation and invest rather quickly. Building on Fudenberg and Tirole (1985), Stenbacka and Tombak (1994) and Hoppe (2000), they model the arrival of the more efficient new technological innovation as a constant-parameter Poisson process in a setting analogous to Section A.2 in the Supplemental Appendix, except that $D[\cdot]$ in equation (A6) depends on the technologies that competing firms adopt.[19] The authors establish that both preemption and attrition type equilibria can emerge, depending on the arrival probability of the more efficient, second technology. An asymmetric equilibrium with dispersed adoption times can emerge, where the second-mover (waiting) is better-off as the more efficient technology becomes available after commitment of the first-mover.

Clark and Conrad (2008) examine a three-stage game between two (risk-neutral) firms engaged in R&D efforts under technological uncertainty to acquire a set of patents that (as a set) can lead to a marketed innovation. Competitors can freely trade the product components they have patented among them. Assuming symmetric Nash bargaining (determining how the surplus arising from one firm eventually commercializing the innovation as a monopolist is shared), the authors illustrate symmetric and asymmetric equilibria that might arise in such a multi-patent contest. They show that products which require (a set of) patents before commercialization might involve a 'hold-up' problem when property rights are fragmented among rivals, which can reduce overall R&D activity unless firms can 'invent around' existing patents of their rivals.

Hsu and Lambrecht (2007) and Leung and Kwok (2012) analyze two-player patent races under asymmetric information. In these models, (a) an incumbent firm and a potential entrant compete for a patent with a stochastic payoff, with the incumbent enjoying monopoly rents in the product market as long as the challenger does not acquire a patent for a substitute product, and (b) the challenger has complete information while the incumbent is 'informationally' disadvantaged in that it does not know the precise value of the challenger's cost. The possibility of losing market share to the new entrant makes the informationally-disadvantaged incumbent invest in the patent inefficiently early; the incumbent consequently not only gives up its option 'value of waiting' but it also loses some of its existing monopoly rents in order to protect its market share.[20] Kulatilaka and Lin (2006) show that potential entrants can be dissuaded from developing substitute technologies if incumbent innovators license out to them patented innovations (instead of keeping them proprietary). This is particularly important when an innovation sets the technology standard for all users (a network effect).[21] Kulatilaka and Lin (2006) show that for financially-constrained innovators, licensing can be employed for raising valuable external funds for R&D and that higher uncertainty sometimes allows the leading innovator to raise more funds. Kulatilaka and Lin (2006, p. 1824) show that royalty licensing schedules inversely linked to demand levels (an observed

[19] In a recent paper by Hagspiel, Huisman and Nunes (2015) involving a single-firm, technology adoption setting, the intensity (Poisson) rate of the new technology arrival can change after each 'last jump'.

[20] In a related paper motivated by liberalization in telecommunication markets, Shibata and Yamazaki (2010) examine the advantages that incumbent firms enjoy over potential entrants, and show how regulation regarding different access charges affects the investment strategy of potential entrants.

[21] Kumar and Turnbull (2008) discuss network effects of patentable *business models*, motivated by court decisions that provide financial institutions the option to seek patent protection for their innovations.

practice in many industries) can be best for the innovator. Finally, in a recent paper, Bhattacharya et al. (2015) focus on the coordination of R&D efforts in bilateral partnerships through a sequential investment game with double-sided moral hazard and outline conditions under which buyout option contracts and milestone-based contracts can achieve the first-best outcome.

3.3 Theme C: Production and Manufacturing Operations

The flexibility inherent in production scheduling, manufacturing operations management (e.g. in-house or outsourced), supply contracts or corporate resource allocation in the face of demand, price or yield uncertainty has been a common focus of RO methods in OR (e.g. see the early work by Li and Kouvelis, 1999, and Kamrad and Ernst, 2001). Table S3 in the Supplement lists 37 contributions under this theme, further divided into two sub-categories.

3.3.1 Flexible systems/expansion, contraction and replacement decisions

Investment in capacity expansion is one of the most critical decisions for manufacturing corporations (Julka et al., 2007), particularly given the irreversibility of substantial committed capital and the uncertainty in production demand. Fontes (2008) considers the dilemma between fixed (dedicated) and more expensive but flexible production systems that allow the exercise of capacity expansion and contraction options as corrective management controls. Similar settings are considered in Lin (2009a,b). Ramasesh et al. (2010) consider mixing flexible and dedicated production processes over different stages in a new product's life cycle (with flexible process employed in the early stages and dedicated later on to achieve cost economies). An interesting application regarding the flexible scale of a hydropower plant is given in Bøckman et al. (2008). Focusing on capacity expansion, Driouchi et al. (2010) argue that path-dependency arises when capacity decisions are based on average (instead of current) product demand, and show how Asian-type real options can be employed in such cases.

On the design of flexible production systems, Gamba and Fusari (2009) examine the ability of the RO approach to tackle modularity (see also Baldwin and Clark, 2000). Using Monte Carlo simulation, Gamba and Fusari (2009) tackle key issues that modularization poses in terms of financial valuation for capital budgeting purposes, while Xu et al. (2012) examine the optimal time of adopting modular production.

Contributions by Robotis et al. (2012) and Bulmuş et al. (2013) study remanufacturing and its environmental (e.g. carbon footprint reduction) and economic benefits (e.g. labor and material savings). In a market where new and remanufactured products are partial substitutes, Robotis et al. (2012) analyze a firm's investment in reusability of its products and setting up collection channels for used products to be remanufactured. They show that the uncertainty of the remanufacturing cost, which hinges on the quality of collected used products, does not hinder such investments if reliable quality inspection is in place. Inspired by the conditions of a car company, Bulmuş et al. (2013) employ a two-stage model with an option in the second stage to remanufacture products collected/returned in stage one, suggesting that remanufacturing is rarely profitable unless it is less capital intensive and less costly than production.

Finally, a number of recent papers deal with the determination of optimal replacement policy for productive assets (equipment or infrastructure). Richardson et al. (2013) consider an infinite-horizon, optimal replacement policy for capital intensive equipment, under stochastic operating and maintenance costs, with a focus on long and uncertain lead times between replacement order and equipment delivery. Reindorp and Fu (2011), Zambujal-Oliveira and Duque (2011), and Adkins and Paxson (2013) examine two-factor models for evaluating capital renewal and determining the optimal equipment replacement policy. Assuming that asset salvage value as well as operating and maintenance costs are stochastic (but uncorrelated), Zambujal-Oliveira and Duque (2011) propose a model of how a 'one-shot' replacement decision should be made, given the asset depreciation schedule (a negative exponential function) and the tax environment. Adkins and Paxson (2013) examine the effect of different depreciation schedules on the optimal asset replacement decision, and show that under stochastic operating and maintenance costs accelerating depreciation schedules do not necessarily incentivize replacement decisions.

3.3.2 Outsourcing, production/resource scheduling and inventory policy

As globalization has reshaped the operations management of both manufacturing and service organizations, outsourcing and ownership alternatives, production planning and resource allocation strategies acquired increased importance in OR (Kouvelis et al., 2001; Bengtsson, 2004; Gunasekaran and Ngai, 2012). For example, option contracts on manufacturing capacity (negotiated bilaterally or via electronic platforms) offer improved risk-sharing and production planning (e.g. Spinler and Huchzermeier, 2006).

Besides contractual options on capacity, several papers have employed real options to evaluate operational alternatives available to manufacturing and service organizations. Szmerekovsky (2007) analyzes single-machine scheduling problems, where task processing times are deterministic but the reward upon completion of each task changes stochastically (according to an arithmetic Brownian motion). Considering three alternative reward objective functions, Szmerekovsky (2007) numerically establishes the effectiveness of branch and bound procedures for handling scheduling of up to 25 tasks.[22] An application of production scheduling in semiconductor manufacturing is given in Chou et al. (2007).

On optimal production and resource allocation, Van Mieghem (2007) offers a single-period theoretical framework that assumes a risk-averse decision-maker with general utility preferences and a set of resources with uncertain end-of-period value, who can allocate resources in either a dedicated, serial or parallel network configuration. Building on portfolio theory, the author shows how the degree of risk aversion and the chosen network configuration drive the allocation of resources so as to mitigate risk through operational hedging and reducing profit variability. He concludes that risk aversion causes over-adjustments in resource positions. Ball et al. (2015) propose a framework to endogenize the interaction of heterogeneous agents who coordinate in a distributed production system. In their model, tasks of various utility upon completion arrive randomly to a task agent who decides which one to allocate/send to a resource agent, based on her preferences. The resource agent can process one task at a time, and

[22] The objective functions considered are maximizing expected NPV, minimizing NPV variance or maximizing the probability of achieving a benchmark NPV.

the time it takes depends on the resource process rate (assumed to follow a square-root, mean reverting process). As the task agent decides which tasks to allocate accounting for the value of waiting for a more profitable task to arrive, the resource agent decides whether to accept (and process) or reject an allocated task based on preferences aligned with system and performance reliability. Both agents evaluate the same (dual) option, but from a different perspective. The authors formulate the problem as a real option game, showing that the production system converges to an equilibrium state that improves the performance for both agents.

A number of reviewed papers focus on specific aspects of managing operations, such as personnel management/labor shifts planning (Qin and Nembhard, 2010; Fernandes et al., 2013) and inventory policies (Berling and Rosling, 2005; Berling, 2008; Secomandi, 2010; Wong et al., 2011; Chen et al., 2015). Qin and Nembhard (2010) propose that in the face of stochastic product demand, costly sequential adjustments to workforce capacity be viewed as a real option, and that efforts to increase workforce agility would allow manufacturers to reduce the sensitivity of production quality to market risks and to better adapt to unexpected market changes. This is important for labor-intensive manufacturers and for enterprises that rely on their workforce to transfer new technologies to marketed products. In a similar setting, Fernandes et al. (2013) show how an optimal mix of regular and temporary worker shifts can be attained while maintaining required service/production levels.

On inventory policy, Berling and Rosling (2005) consider typical fixed replenishment quantity (R, Q) policies in a real options framework. Assuming the Consumption CAPM holds (Breeden, 1979), the authors suggest simple adjustments to R and Q to account for the systematic risk component of stochastic demand and stochastic purchase price (both following a gBm). They conclude it is the systematic risk of the purchase price (not demand) that has a significant effect on optimal policy. In later work, Berling (2008) examines the same problem, assuming deterministic demand and that the log of purchase price follows a (stationary) Ornstein-Uhlenbeck process, an intuitively more appealing assumption for price evolution.

Secomandi (2010) examines optimal inventory-trading policy for a risk-neutral merchant that stores energy and natural resources such as natural gas in a warehouse with space and injection/withdrawal capacity limits. He shows that if the resource spot price evolves according to an exogenous Markov process, the optimal inventory-trading policy involves two (price and stage-dependent) stock targets that partition the available inventory/price space at each stage into three regions: one where it is optimal to buy and inject, one where it is optimal to do nothing, and one where it is optimal to withdraw and sell the resource to the market. In parallel work with co-authors (see Lai et al., 2010), an extension involving multidimensional models for the evolution of the entire natural gas forward curve is studied. Although this leads to an intractable problem, Lai et al. (2010) compute lower and upper bounds for the value of gas storage and use them to benchmark a set of heuristics used by practitioners to value storage options. More recently, Nadarajah et al. (2015) develop a novel approximate dynamic programming approach for the real option management of commodity storage, using the Lai et al. (2010) problem setting. . Felix and Weber (2012) apply dynamic programming on numerically constructed multinomial recombining trees to the valuation of gas storage, while Lai et al. (2011) propose a heuristic valuation of the option to store liquefied natural gas in the presence of a wholesale market. The structure of the optimal policy in Secomandi (2010) implies that the operational, inventory and trading decisions are interlinked. Chen et al. (2015) similarly examines interlinked inventory planning and operations in the context of oil refineries. In a discrete, one-period setting, Skintzi et al. (2008) consider a manufacturer's dilemma between investing in a warehouse facility or outsourcing warehouse operations to a specialized firm. They suggest an 'in-between, flexible' alternative, where the manufacturer incurs the warehouse investment cost and then leases the warehouse to the specialized firm.

On outsourcing operations, Li and Wang (2010) consider the problem of reserving production capacity, both in-house and abroad, by a risk-averse manufacturer that wishes to satisfy domestic uncertain demand in the face of fluctuating exchange rates. They show that manufacturing firms may choose to carry local excess production capacity, even with a negative marginal contribution to profits, as a means of operational hedge against unfavorable exchange rate movements. The value of this operational switching option increases with demand and exchange rate uncertainty. Moon et al. (2011a) examine the dilemma between outsourcing and forming a joint venture in a real options framework, while Takezawa et al. (2007) consider the situation where a publicly traded firm spins-off a manufacturing subsidiary through an IPO; it also agrees to buy certain quantities from the span-off subsidiary at a pre-specified price via a forward supply contract. The parent decides the optimal capital structure for the spin-off (parent firm equity position) and the forward contract terms to maximize its shareholders' value. Appropriate use of the forward supply contract allows for a wider range of choices among admissible capital structures.

In related work, Benaroch et al. (2012) characterize the thresholds between (costly reversible) outsourcing and back-sourcing as real options under demand uncertainty. Antelo and Bru (2010) stress the informational benefits that outsourcing production temporarily may have for a firm that considers downsizing or refocusing its operations. A high-cost producing firm can incur fixed restructuring costs to reduce its producing cost to an intrinsic (but unknown) industry level, or outsource production to an external, more cost-efficient firm with industry-level marginal cost of production. Due to incomplete information about the true industry marginal cost of production, for a moderate range of restructuring costs, the firm finds it optimal to use outsourcing temporarily to gain information on industry marginal costs and only afterward incur the necessary restructuring costs.

3.4 Theme D: Supply Chain and Logistics

The configuration of supply chains and the optimal contracting arrangements among various supply chain parties have been an important focus of ongoing research efforts that employ real options modelling and bargaining/game-theoretic tools. Table S4 (Supplementary material) lists our 29 reviewed contributions chronologically.

3.4.1 Flexibility in supply chain contract terms

Real Options provide an intuitive way of incorporating flexibility in the management of supply chain operations (Wallace and Choi, 2011). Kamrad and Siddique (2004) and Burnetas and Ritchken (2005) provide important early contributions that evaluate the flexibility inherent in supply chain contracts using real options. Kamrad and Siddique (2004) analyze "supply contracts in a setting characterized by exchange rate uncertainty, supplier-switching options, order-quantity flexibility, profit sharing, and supplier reaction options*"* (p. 64). A producer facing capacitated production and inventory ability requires a production input (component or raw material) that can be supplied by M different suppliers. The producer can adjust the production rate over time and (as suppliers might be abroad) the order quantities from each supplier in the face of fluctuating exchange rates so as to meet product demand. Suppliers require a supplier-specific penalty if producer order-level changes exceed a certain level. Assuming a model based on equations (A1) and (A2) in the Supplementary Appendix, with $m_j\left(t, Y_j(t)\right) = \mu_j Y_j(t)$ and $s_j\left(t, Y_j(t)\right) = \sigma_j Y_j(t)$, for the stochastic evolution of exchange rates (and existence of an FX futures market), the authors express the optimal policies for the producer-supplier contracts as the solution of a system of $M+1$ Bellman equations using no-arbitrage arguments. Their approach endogenizes profit-sharing, which is allowed to be time variant (unlike previous work by Li and Kouvelis, 1999) and intuitively highlights that suppliers essentially hold compound "reaction" options to address the order-quantity risk generated by the producer's flexibility to switch among suppliers. In a similar setting, Liu and Nagurney (2013) consider supply chain networks with multiple offshore suppliers and *multiple* manufacturers facing demand and cost uncertainty, and examine how these affect the willingness of manufacturers to invest in quick-response production capabilities. They formulate and solve the general problem via variational inequalities, showing that (a) the sourcing cost manufacturers without quick-response production capability are willing to pay increases with demand uncertainty, and (b) manufacturers with (respectively, without) quick-response production capability are more profitable when demand is high (low). In a recent empirical paper, Osadchiy et al. (2015) show that the structure of supply chain networks affects the systematic risk of chain members, mediating the effect of economy-wide shocks on industry or firm sales.

Burnetas and Ritchken (2005) consider a setting with one manufacturer whose only access to the product market is via a single retailer. In industries characterized by long lead times, high demand uncertainty and short selling seasons (such as apparel, toys, etc.), it is common for manufacturers to provide retailers *reordering* (call) *options* that allow purchasing additional goods at a fixed price for a set time; they also provide retailers *return* (put) *options* that give the right to return unsold goods at a set salvage price. The manufacturer's problem is to design the terms of the reordering and return options and establish their prices, along with the wholesale price. The authors highlight that valuation of these options is different from the usual Black-Scholes-Merton setting (where exercise of new options does not affect the underlying asset price). As the underlying asset in this setting is the good supplied by a monopolist, its wholesale price is affected by whether or not options are offered to the retailer, whose optimal exercise actions have a "feedback effect" on the profit of the monopolist. Assuming a one-period world with a linear inverse demand function and a Bernoulli process for the uncertain end-period demand realization, Burnetas and Ritchken (2005) show that the granting of options by the manufacturer achieves better supply-chain co-ordination and diminishes retail price volatility, but it could also harm the retailer's profitability in case of high demand uncertainty.

Wang and Tsao (2006) examine a similar problem from the retailer's perspective, under the assumption of uniformly distributed demand. Wang et al. (2012) also stress the possibility that, under certain conditions, order-quantity call options can be detrimental to the retailer's overall performance. Wu et al. (2010) consider the effect of risk aversion on the manufacturer's optimal decisions, while Gu and Zhang (2012) investigate possible default by a firm that has entered a long-term contract with a supplier who essentially acts as a firm debtor.

In Zhao et al. (2013), one or more retailers can complement their order call options with immediate purchases from a spot market (such as a business-to-business, B2B, e-marketplace). Assuming manufacturers and retailers are price-takers in the spot market (no "feedback effect") and abstracting from their risk-preferences, the authors provide a value-based pricing scheme for order options in the supply chain. Inderfurth and Kelle (2011) also consider the optimal mix of long-term procurement contracts and spot market orders, while in Wu and Kleindorf (2005) one buyer and multiple sellers may either contract for delivery in advance or they may buy and sell some or all of their input or output in the spot market. Assuming risk-neutrality and heterogeneous sellers with perfect knowledge of the buyers demand function, the authors characterize the price of capacity options, the value of managerial flexibility and the efficiency and sustainability of B2B exchanges.

3.4.2 Timing and alternative supply-chain configurations

Along a typical supply chain, the rights of buyers and sellers to choose the time to transact and the information set on which they base such decisions have been analyzed as real option games in a negotiation/bargaining setting. Assuming that the revenue and the cost for a buyer and a seller follow correlated gBms, Moon et al. (2011b) develop a bilateral negotiation model where both the seller and the buyer have an option to determine when to sell and buy, which may influence negotiation outcomes. The authors show that considering the parties' timing options narrows the traditional 'implicit zone of possible agreement' (IZOPA) and lowers the probability of reaching an agreement.[23] Zheng and Negenborn (2015) show that the IZOPA widens with the buyer's elasticity of demand. Wang et al. (2015) extend the work of Moon et al. (2011b) allowing for two sellers and two buyers, with the possibility of mergers in either the downstream or upstream firms. They show that the IZOPA is unambiguously decreasing in the correlation of manufacturers' revenues, while the synergy and diversification effects brought-forth by mergers have an ambiguous impact.

Yan and Dooley (2010) consider the timing of trading in a secondary market for inventory updating purposes by a buyer in a supply channel, showing that optimal timing depends on the retail margin, prior information quality and demand volatility.[24] Löffler et al. (2012) analyze how asymmetric information between a buyer and a seller in a supply chain affects the timing of contracting. In a discrete-time, two-stage setting they show that under symmetric information delayed contracting is first-best and abandoning established supplier relationships never occurs. In contrast, under asymmetric information, early contracting with potential abandoning can be value-enhancing. Chen (2012) considers cooperative optimal timing of setting up a supply chain channel involving fixed investment by two cooperating parties. Collaboration between a manufacturer and a supplier in the context of high technology industries is also addressed in Dulluri and Srinivasa Raghavan (2008).

[23] For the traditional implicit zone of possible agreement in negotiations (IZOPA), see Sebenius (1992).
[24] Oh and Özer (2013) focus on the role of time in forecast information sharing in a setting where a supplier attempts to elicit credible forecast information from a manufacturer, when both parties gain asymmetric demand information for the end product over multiple periods.

Regarding alternative supply chain configurations, Graves and Willems (2005) consider optimal strategies for setting up the supply of new products. These strategies involve multiple options (e.g. choosing suppliers, modes of transportation to points of sale, options to manufacture or assemble parts etc.) that are differentiated by their lead time and direct cost added. A wide variety of other formulations arising in specific contexts or sectors have appeared in the reviewed period and journals; these range from the option to offer a low-price guarantee to customers (Marcus and Anderson, 2006), options on tickets of sporting and entertainment events (Cui et al., 2014), real-time handling and call-back options in customer contact centers (Armony and Maglaras, 2004a,b), to the valuation of maritime, time charter contracts viewed as compound real options (Al sharif and Qin, 2015) and booking limits for capacity control in airline alliances (Graf and Kimms, 2011, 2013).

3.5 Theme E: Energy, Natural Resources and the Environment

This theme has been a classic topic for real options research since its inception due to staging of decisions, long horizons and the high uncertainties involved (see e.g. early work in OR by Tseng and Barz, 2002). We sub-divide the 22 reviewed contributions of this theme into two categories (see Table S5).

3.5.1 Energy, infrastructure and deregulation

The deregulation of infrastructure industries, such as energy and telecommunications, has exposed incumbent (national) monopolistic firms to fierce competition and new risks. In a paper focused on liberalization in telecommunication markets, Shibata and Yamazaki (2010) examine the advantages that incumbent firms enjoy over potential entrants and how regulation regarding different access charges affects the investment strategies of potential entrants.[25] Building on this work (and that of Kort et al., 2010) Siddique and Takashima (2012) model rivalry in a deregulated industry with stochastic (liberalized) output price and lumpy, modularized capacity investment. In a two-stage real options game, they show numerically that the value of a duopolist in a 'proprietary-knowledge' setting (with strong patent protection) is lower than in a 'spillover-knowledge' setting (with weak patent protection), which has interesting implications for policy makers in liberalized markets.

In deregulated electricity markets, Thompson et al. (2004) propose an algorithm for the valuation and optimal operation of hydroelectric and thermal power generators, incorporating a wide class of electricity spot price models and the price spikes that are typical in electricity markets. Similarly, Tseng and Lin (2007) use a lattice framework of correlated electricity and fuel prices to value a power plant whose generating units can be committed to production on an hourly basis. Farzan et al. (2015) analyze the

[25] Clark and Easaw (2007) propose that the optimal access price is the certainty equivalent of expected risky project cash flows that rewards the network provider for undertaking the risky infrastructure investment. Baecker et al. (2010) analyze access pricing in the context of the German telecommunications market, while Franklin Jr. (2015) evaluates the impact that delayed installment of different network elements in a mobile telecommunications network has on mobile service costs.

optimal operation and suspension of electricity micro-grids employing renewable (solar photovoltaic) and non-renewable (natural gas) sources of generation. Different aspects of investments in wind power generation can be found in the case studies by Muñoz et al. (2011) and Boomsma et al. (2012). Scandizzo and Ventura (2010) consider possible equilibria between a public and a private firm that negotiate a concession agreement for the exploitation of a certain investment, such as a motorway concession.

In biofuels, Li et al. (2015) evaluate an investment in new technology for producing cellulosic biofuels subject to construction lags and uncertain fuel (gasoline) prices, modeled as a geometric mean-reverting process. Bastian-Pinto et al. (2010) provide an interesting analysis of the 'flex fuel car' that provides the option to choose between ethanol and gas at each refueling stop using Monte Carlo simulation.

3.5.2 Natural resources, land and the environment

The valuation of timber harvesting options using a contingent claims approach has received much attention in land economics, since the ability to harvest a forest stand right away or delay its harvesting in response to timber price fluctuations resembles an American-style call option. Ownership of a forest stand gives the right to obtain the timber by incurring the harvesting cost and sell it on the open market at the prevailing prices. A twist is that the forest can be re-planted after each harvest, creating a new harvest option.

Petrasek et al. (2015) further consider that each year a forest stand goes unharvested, its owner is able to sell carbon offset credits in the emissions market. This provides a (stochastic) supplementary income that, combined with timber revenues, should actually determine the optimal harvest time. Assuming timber and carbon credit prices follow correlated mean-reverting processes, they show that considering the carbon-related supplementary cash flows from the emissions market would lead to higher forest land values and shorter harvest cycles (ages). Messina and Bosetti (2006) similarly analyze land conversion problems, while Heikkinen and Pietola (2009) apply a Markov-decision process to a case study in Finnish agriculture. Lukas and Welling (2014) consider eco-friendly investments in supply chains, showing that under uncertainty, economic and ecological efficiency are mutually exclusive. In a real option game where two supply chain parties sequentially negotiate an eco-friendly joint investment, they show that the negotiation outcome is neither economically nor ecologically efficient and it becomes worse with additional chain links (n-party extension).

From an environmental policy perspective, Ohyama and Tsujimura (2008) formulate the decision of agents to implement an emission-reducing policy as a leader-follower game, similar to the one in Supplementary Appendix Section A.2, while Di Corato and Montinari (2014) deal with a municipality's decision to complement its landfilling waste management with recycling, establishing the optimal time to incur the recycling set-up costs and the optimal share of waste to be recycled.

Most of the above studies assume away the difficulty of estimating the appropriate discount rate for environmental (or land-use) alternatives, despite the multi-generational impact and long-term externalities of such alternatives. Kunsch et al. (2008), motivated from a case study in radioactive waste management, propose a way to handle this, based on the Black and Scholes (1973) model.

3.6 Theme F: Valuation and other topics

The last theme combines work on valuation and various other topics not covered above (see Table S6 in the Supplement). The link between RO valuation and traditional decision tree analysis (DTA) is examined in Brandão and Dyer (2005), while Reyck et al. (2008) integrate DTA and the certainty-equivalent version of NPV in a RO framework that does not rely on the 'replicating portfolio-spanning' assumption. Wallace (2010) further discusses similarities and differences between RO theory and stochastic programming.

In a general project valuation setting, Keswani and Shackleton (2006) show how incremental levels of investment and divestment flexibility enhance the project's NPV, while Borgonovo et al. (2010) propose a novel measure for conducting sensitivity analysis in the valuation of large-scale industrial projects. In terms of RO valuation methods, Hahn and Dyer (2008) show how the work of Nelson and Ramaswamy (1990) on recombining binomial lattices can be extended and applied to model dual correlated mean-reverting processes, typically used to evaluate switching options in natural resources/energy. Wahab and Lee (2011) propose a multi-layered, multinomial lattice approach that discretizes the process followed by a regime-switching underlying asset (following a different gBm in each of the n regimes). They apply this to swing options to change the volume of periodic deliveries of a commodity on certain dates in the future. Folta et al. (2010) analyze hybrid entrepreneurship, i.e. an individual's incremental transition (as opposed to full, one-off immersion) to self-employment from a waged job, as a real switching option. Using matched employee–employer data, the authors examine a sample of Swedish wage earners from the knowledge-intensive sector, providing evidence that such hybrid entrepreneurial forms represent a significant proportion of transitions into and out of entrepreneurship, validating RO theory predictions.

More recently, Wang and Dyer (2102) propose a general framework based on copulas for modeling dependent multivariate uncertainties with arbitrary distributions via the combined use of decision trees and real options. Their dependent decision-tree approach approximates the underlying copula with uniform variables and then transforms it into the desired multivariate probability tree which possesses the required marginal distributions and correlation structure.

Zmeškal (2010) combines fuzzy set theory with binomial real options valuation where all lattice inputs are given vaguely in the form of fuzzy numbers, while Ghosh and Troutt (2012) propose and provide a software toolkit that operationalizes complex (compound real) option models for practitioner use. Finally, Brandão et al. (2012) discuss the difficulties in obtaining unbiased estimates of project volatility (undeniably the most critical input for RO applications). For project cash flows well-approximated by a gBm process, proper accounting for the temporal resolution of uncertainty and updating of conditional expectations can ameliorate known upward biases that volatility estimates obtained through MC simulation exhibit. Extensions for leveraged project cash flows (due to fixed operating costs) and non-constant volatility are also addressed.

In other related topics, a few experimental studies analyze the attitudes of individuals towards (investment) options. Shin and Ariely (2004) consider options that might be unavailable unless sufficient effort is invested in them, asking whether the threat of disappearance changes the way people value such options. They find that decision-makers invest more effort and money in keeping options open that might disappear, even when the options themselves seem to be of little value. Their findings suggest that the tendency of keeping one's options 'open' is likely driven by a type of aversion to loss (Kahneman and Tversky, 1979). Du and Budescu (2005) suggest that human aversion to vagueness might explain deviations from the 'expected utility maximization' model. Subjects were asked to price (or choose) among investment options that varied in vagueness (on probabilities and/or outcomes) and domain (gains or losses). Results suggest that individuals' attitudes towards vagueness are influenced by the reference domain, exhibiting "reversals of attitudes" towards vagueness, particularly in the 'gains' domain.

Glasserman and Wang (2011) analyze the Capital Assistance Program (CAP) initiated by the U.S. government in February 2009 to provide backup capital to qualifying financial institutions that could not raise sufficient capital from private investors. Under CAP, participating banks would sell convertible preferred securities and warrants on bank common shares to the U.S. Treasury. The authors value these preferred securities and the embedded options. The interesting aspect of the program design was that it provided the issuer and the buyer options, since conversion (by the issuing bank) and warrant exercise (by the buying Treasury) both cause significant dilution of common shares. The program is evaluated as a dynamic stochastic game between the parties involving a modified binomial model for the issuer's equity to capture dilution and a determination of the optimal buyer/issuer strategies. The authors' estimates suggest that the terms of the CAP provided substantial benefit to the issuer, while no banks participated in the program.

4. Concluding remarks and directions for future research

Since the 1990s, operations research has relied on Real Options as a valuable problem-formulation and problem-solving tool for improving managerial decision-making. Since then, a steady increase in papers applying RO has appeared in OR journals.

In this article, we provide a contemporary and extensive review of influential articles in five select OR journals that employ the RO approach during the last 12 years. Our extensive review of 164 research papers over the 2004-2015 period provided trends and evidence concerning the significant increase and contribution of RO-related papers. We have identified six main subject themes (OR sub-topics) where use of the RO approach has been most prominent and fruitful.

By cataloguing the research contributions within each identified theme and identifying their common characteristics, our review provides confirmation that, besides investment timing problems, key issues in manufacturing (such as capacity expansion and contraction, production scheduling, storage and outsourcing) and in supply chain management (such as bilateral options and flexibility in adjusting the composition of suppliers) have been prominently influenced by and benefited from RO.

The fit of RO with OR has shed light on a number of important operations research issues and helped improve our understanding of the value of flexible management decisions. Yet there remain a number of critical questions that need to be addressed, suggesting paths for future research. In our view, the following are fruitful areas for directing future research efforts:

(a) Extending work on "exceptions" to the standard optimal investment rule of RO theory. This is important to bring the theory closer to (and enabling its wider adoption in) practice since practitioners seldom invest at investment thresholds as high as pure RO theory indicates using standard parameter values. Understanding the situations that create a "wedge" (or extra opportunity cost), such as holding cost, rising investment costs and proper accounting of competitive reactions is essential in this effort.

(b) Extending work on sequential investments and joint timing and capacity (scale) choices. Models of investment timing and capacity expansion typically assume that capacity additions are either 'lumpy' (e.g. Kort et al., 2010) or infinitesimal (e.g. Murto et al., 2004). This division extends to multi-firm settings, such as in option games (see the discussions in Chevalier-Roignant et al., 2011; Azevedo and Paxson, 2012) and requires bridging such that capacity changes in infinitesimal increments are reconciled as a limiting case of 'lumpy' investments in a more transparent way. We encourage further research establishing this link, which can facilitate both further theoretical work and more practical applications. We also encourage additional work that simultaneously considers joint determination of timing and scale choices in a competitive environment.

(c) Better integration among distinct OR models. Models capturing the flexibility inherent in production scheduling and resource allocation can be better integrated with models involving the strategic use of excess (safety) capacity and inventory levels for operational hedging purposes. Extending promising work in single-period settings (e.g. Van Mieghem, 2007) and on the inventory/operations intersection (e.g. in energy and natural resources, see Secomandi, 2010; Lai et al., 2010), multi-period models that combine operations scheduling with capacity and inventory choices and constraints seem fruitful areas. A possible approach might involve formulating models in specific contexts.

(d) Analysis of negotiations and collaborative decision-making in supply chains. Building on our understanding of bilateral, supply (e.g. reordering and return) options and of the flexibility inherent in order-quantity choices and supplier switching (e.g. Kamrad and Siddique, 2004; Burnetas and Ritchken, 2005; Graves and Willems, 2005; Liu and Nagurney, 2013; Zhao et al., 2013), we see a fruitful and promising area for future research in the analysis of negotiations and collaborative decision-making in supply chains (Moon et al., 2011b; Banerjee et al., 2014; Zheng and Negenborn, 2015; Wang et al., 2015). The environmental aspect of collaborative carbon footprint reduction along a supply chain channel (and its effects on how production is organized, see Robotis et al., 2012; Bulmuş et al., 2013) will likely become more important as customers and firms get more conscious of environmental issues or are more socially responsible.

(e) Integrating investment and financing decisions and addressing related agency problems. In many investment settings there have been efforts to unify investment and financing decisions (e.g. Shibata and Nishihara, 2015; Morellec et al., 2015). At the same time, principal (owner) and agent (manager) incentives and contracts have been analyzed under incomplete or asymmetric information structures (e.g. Delaney and Thijssen, 2015.). Analogous agency conflicts that plague principal and agent relations *inside* the firm likely affect the firm's contracting with *outside* providers of debt financing (private or public) or its outsourcing partners. Do information asymmetries among managers and owners, debtors and other outside partners provide incentives for managers to distort leverage or outsourcing policies away from the 'equity value maximizing' levels and what contractual terms inside or outside the firm can ameliorate these incentives? What are the investment rate and timing implications of such incentives?[26]

(f) Encouraging more empirical work and case studies. The number of empirical studies and case applications has been rather low (21 out of the 164 articles reviewed or 13% overall). In OR, less than 10% (3/31) of theme A are empirical; in C and D about 20% (8/37 and 6/29). In B 33% (10/30), and only in theme E (Energy & the Environment) there is a substantial representation (13/22 or 59%). More empirical work is clearly needed, especially in themes A, C and D, to confirm or negate the predictions of the RO approach in the OR field. Although large databases usually available for empirical work in finance have not been of that much help for empirical work on RO in OR, as more OR relevant databases and data sets become available, such as on corporate micro-level IT investments, firm patents and other intellectual capital, start-ups, venture capital and financing rounds, researchers working on empirical tests of RO theory in subject areas relevant to OR will find their work welcomed by the OR community. Examples of empirical work that may be a useful starting base for readers interested in starting new research in this area include Dewan et al. (2007), Ziedonis (2007), Folta et al. (2010), and Liu and Wong (2011), among others checked under the empirical column in our classification table (e.g. Chance et al., 2008; Glasserman and Wang, 2011). Previous empirical work includes Quigg (1993), Moel and Tufano (2002), Secomandi (2010), and Fleten et al. (2016, 2017). Case studies are even more rare than empirical studies, and in need of further encouragement (e.g. Marcus and Anderson, 2006; Messina and Bosetti, 2006; Boomsma et al., 2012 and Dimakopoulou et al., 2014, to name a few). We hope that the limited number of published case applications and papers motivated by industry or sector-specific problems in the period and journals we reviewed can act as a valuable base for theorists working on more in-depth and practically-relevant models and frameworks.

(g) Facilitating more realistic applications. Recent advances in modeling dependent multivariate uncertainties for RO valuation (e.g. via copulas, as in Wang and Dyer, 2012, or via more general systems of stochastic processes or the use of variational inequalities), along with operational enhancements in estimating volatility and other key inputs (e.g. Brandão et al., 2012) and extending the use of numerical tools such as Monte Carlo simulation (e.g. Hahn and Dyer, 2008; Bastian-Pinto et al., 2010; Ghosh and Troutt, 2012) should enable and encourage more realistic applications of RO in OR problems.

[26] The initial definition of real options promoted by Myers (1977) focused on "corporate assets". Subsequent principal-agency problems in debt financing and their interaction with the investment decision could be viewed as appropriate extensions of real options. This distinction is somewhat arbitrary. Many of the mathematical formulations regarding liability options are similar to corporate asset options.

It is our aim and hope that this review will be useful to OR researchers in addressing the above challenging issues and spur more work that will augment the impact of RO in OR.

Supplementary material: Supplementary material associated with this article including a Supplementary Appendix with a general modeling framework can be found in the accompanying file entitled '*EJOR_ROinOR_Supplement.pdf*'

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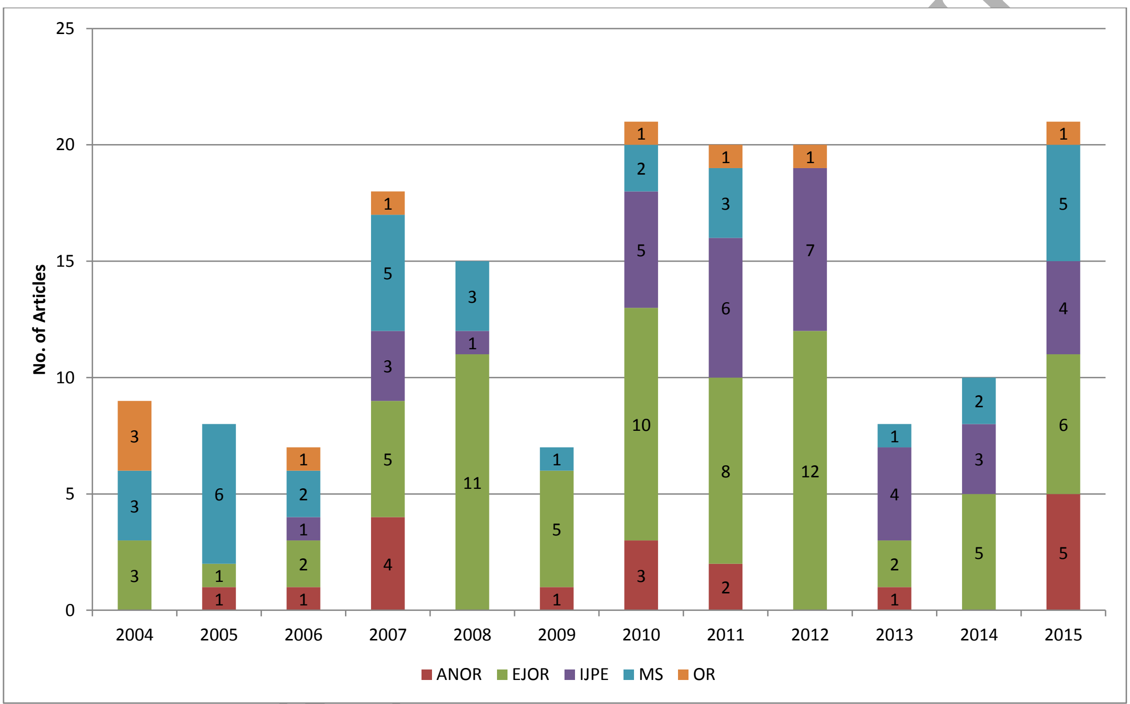
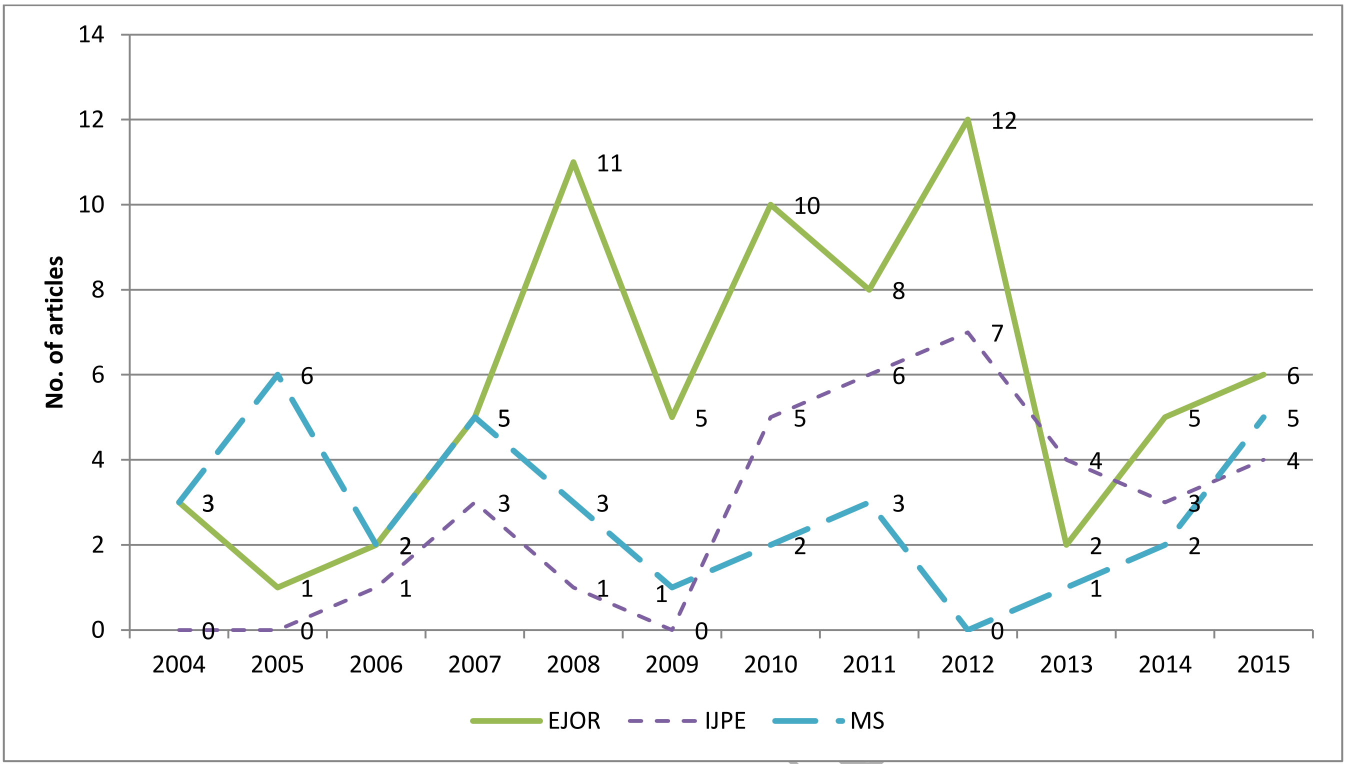
Figure 1: The Figure plots the number of 'Real Options' (RO) related articles published by each reviewed journal in each year during the 12-year period covered (from 2004 to 2015). In Panel A, the total number of published research articles per year is shown. In Panel B, the evolution of each journal's publications on the topic over time can be seen. ANOR is Annals of Operations Research, EJOR is European Journal of Operations Research, IJPE is International Journal of Production Economics, MS is Management Science, and OR is Operations Research.

Panel A: Number of RO related published research articles per year by each covered OR journal.



Panel B: Evolution of each reviewed OR journal's publications coverage on the topic of Real Options (RO) over time.



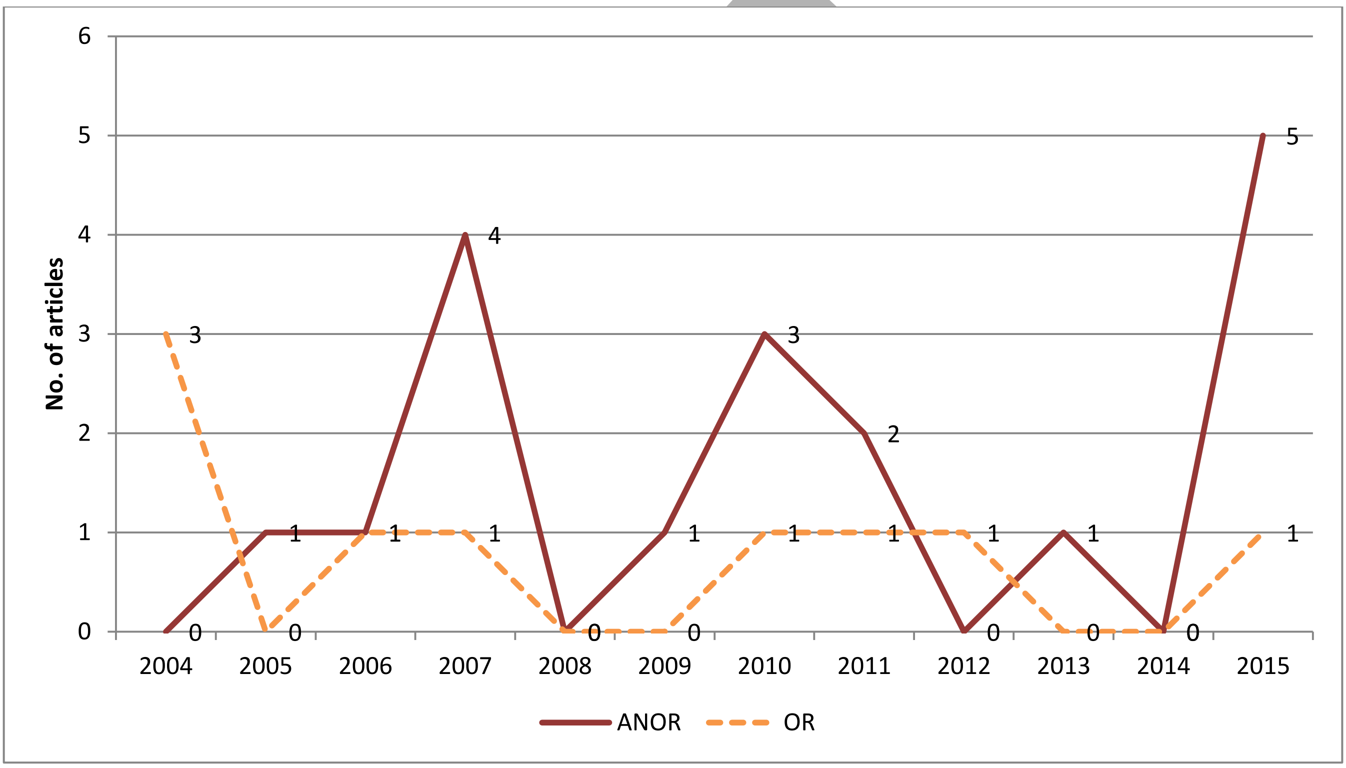


Figure 2: The Figure plots the number of 'Real Options' (RO) related articles published per identified subject theme (Theme A-F) as it evolved over the last two consecutive six-year subperiods (2004-2009 and 2010-2015).

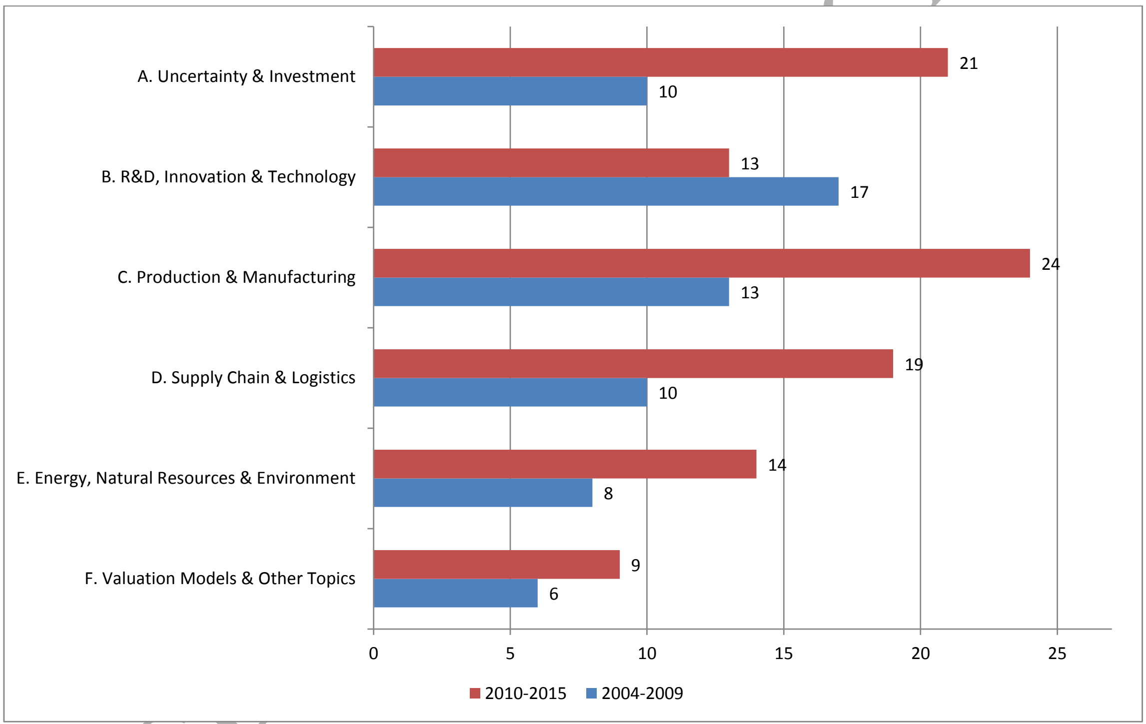


Figure 3: Number of published Real Options articles per subject theme per OR journal. EJOR is European Journal of Operations Research, IJPE is International Journal of Production Economics and MS is Management Science.

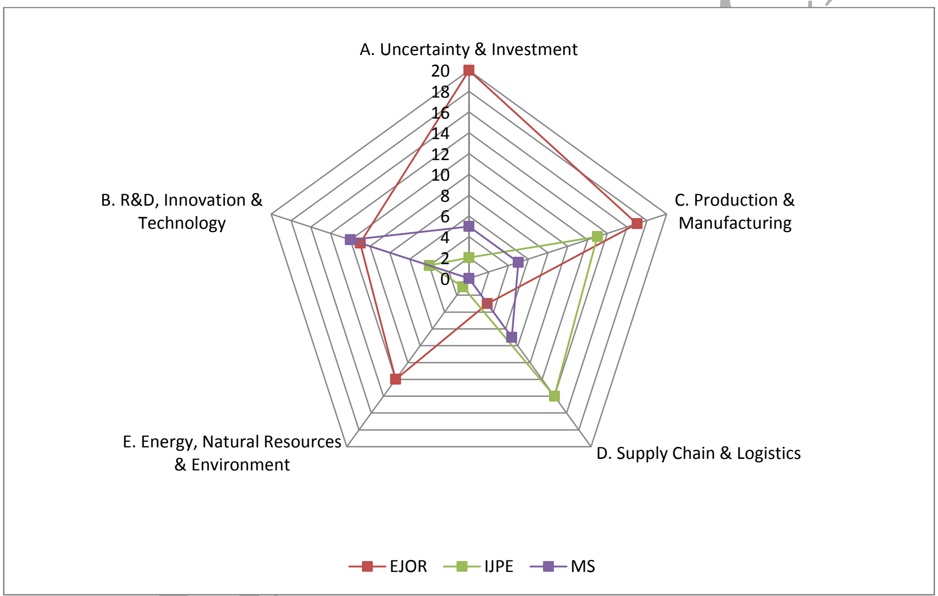


Table 1: The Table reports the number of 'Real Options' (RO) related research articles published from 2004 to 2015 by each covered OR journal per general subject theme identified, as follows: (A) Uncertainty & Investment, (B) R&D, Innovation & Technology, (C) Production & Manufacturing, (D) Supply Chain & Logistics, (E) Energy, Natural Resources & Environment, (F) Models & Other Topics. Percentages (out of 164 papers reviewed) are reported in parentheses. ANOR is Annals of

Operations Research, EJOR is European Journal of Operations Research, IJPE is International Journal of Production Economics, MS is Management Science, and OR is Operations Research.

Theme	ANOR	EJOR	IJPE	MS	OR	Total
A. Uncertainty & Investment	3 (2%)	20 (12%)	2 (1%)	5 (3%)	1 (1%)	31 (19%)
B. R&D, Innovation & Technology	3 (2%)	11 (7%)	4 (2%)	12 (7%)	0 (0%)	30 (18%)
C. Production & Manufacturing	0 (0%)	17 (10%)	13 (8%)	5 (3%)	2 (1%)	37 (23%)
D. Supply Chain & Logistics	2 (1%)	3 (2%)	14 (9%)	7 (4%)	3 (2%)	29 (18%)
E. Energy, Natural Resources & Environment	7 (4%)	12 (7%)	1 (1%)	0 (0%)	2 (1%)	22 (13%)
F. Valuation Models & Other Topics	3 (2%)	7 (4%)	0 (0%)	4 (2%)	1 (1%)	15 (9%)
Total	18 (11%)	70 (43%)	34 (21%)	33 (20%)	9 (6%)	164 (100%)

Table 2: The Table lists and categorizes the 164 articles that are reviewed in the 5 covered OR journals from 2004 to 2015 across several dimensions. The first major categorization is between single-firm setting coverage (Panels A.1-A.2) and multi-firm, game-theoretic settings (Panels B.1-B.2). Articles are further separated into Panels depending on whether their context (setting and contributions) is of general applicability (General context) or is a specific context (e.g. case study or industry-specific problem). In all four Panels (A.1-B.2), Theory refers to whether a reviewed article proposes a new theoretical model/ framework or whether it provides refinement(s) of existing theoretical approaches. If a reviewed article has an empirical focus or includes an applied section, it is marked with ✓ on the Empirical or Applied dimension. Information refers to whether agents possess complete information or not (incomplete). Under Authors' Keywords, select keywords the authors themselves have used are summarized. Keywords 'real options' and 'uncertainty' have been omitted.

Panel A.1: Single-firm, General context

Article	Citation	Journal	General Theme	Theory		Empirical or Applied	Information		Principal/	Authors'
No.	Authors (Year)	Acronym	Topic	New	Refine		Complete	Incomplete	Agent	Keywords
1	Adkins and Paxson (2013)	EJOR	C. Production & Manufacturing		✓		✓			Equipment replacement; Tax depreciation
3	Alexander et al. (2012)	EJOR	A. Uncertainty & Investment		✓		✓			Investment; Arithmetic Brownian motion
5	Arkin and Slastnikov (2007)	ANOR	A. Uncertainty & Investment		✓		✓			Corporate taxation; Depreciation policy; Tax revenue
13	Battauz et al. (2015)	MS	A. Uncertainty & Investment	✓			✓			Investment; Gold loan; Collateralized borrowing
15	Berling (2008)	EJOR	C. Production & Manufacturing		✓		✓			Inventory; Holding cost
16	Berling and Rosling (2005)	MS	C. Production & Manufacturing		✓		✓			Inventory; Holding cost
18	Bobtcheff and Villeneuve (2010)	EJOR	B. R&D, Innovation & Technology		✓		✓			Investment; Technology
21	Borgonovo et al. (2010)	EJOR	F. Valuation Models & Other	✓		✓	✓			Investment; Sensitivity analysis
22	Brandão and Dyer (2005)	ANOR	F. Valuation Models & Other		✓	✓	✓			Lattice methods; Decision trees
23	Brandão et al. (2012)	EJOR	F. Valuation Models & Other		✓	✓	✓			Investment; Volatility; Simulation
27	Chan et al. (2007)	MS	B. R&D, Innovation & Technology		✓		✓			Project selection; Technology
28	Chance et al. (2008)	MS	B. R&D, Innovation & Technology		✓	✓	✓			Innovation; Bayesian update; Movie revenues; Box office receipts
32	Chiu et al. (2015)	ANOR	A. Uncertainty & Investment	✓		✓	✓			Stock loan; Regime switching; Recallable air ticket; Launch of fashion product
34	Chronopoulos et al. (2011)	EJOR	A. Uncertainty & Investment		✓		✓			Investment; Operational flexibility; Risk aversion
37	Clark and Easaw (2007)	EJOR	E. Energy, Natural Resources &		✓		✓			Network access pricing

			Environment							
39	Delaney and Thijssen (2015)	EJOR	A. Uncertainty & Investment		✓				✓	Voluntary disclosure; Sub-optimal investment
40	Dewan et al. (2007)	MS	B. R&D, Innovation & Technology			✓	✓			IT investments; Risk-return
43	Dias and Shackleton (2011)	EJOR	A. Uncertainty & Investment		✓		✓			Switching option; Hysteresis; Interest rate uncertainty
45	Dong et al. (2014)	IJPE	A. Uncertainty & Investment		✓		✓			Operational flexibility; FX uncertainty
46	Driouchi et al. (2010)	EJOR	C. Production & Manufacturing		✓		✓			Path-dependence; Capacity
47	Du and Budenscu (2005)	MS	F. Valuation Models & Other			✓		✓		Vagueness; ambiguity aversion
48	Du et al. (2007)	EJOR	A. Uncertainty & Investment		✓	✓		✓		Optimal advertising policy
52	Fernandes et al. (2013)	EJOR	C. Production & Manufacturing		✓		✓			Investment timing; Manpower planning
54	Fontes (2008)	EJOR	C. Production & Manufacturing		✓		✓			Fixed and flexible capacity investments; Costly reversibility
56	Gamba and Fusari (2009)	MS	C. Production & Manufacturing		✓		✓			Modularity; LS Monte Carlo
58	Ghosh and Troutt (2012)	EJOR	F. Valuation Models & Other		✓		✓			Compound options; Practitioner relevance
62	Graves and Willems (2005)	MS	D. Supply Chain & Logistics		✓	✓	✓			Multi-stage supply chain configuration
64	Gunasekaran and Ngai (2012)	IJPE	C. Production & Manufacturing		✓		✓	✓	✓	Review article; Operations Management
66	Hackbarth et al. (2014)	MS	A. Uncertainty & Investment	✓			✓			Investment; Product market options
67	Hagspiel et al. (2015)	EJOR	B. R&D, Innovation & Technology		✓		✓			Innovation; Technology adoption
68	Hahn and Dyer (2008)	EJOR	F. Valuation Models & Other	✓			✓			Energy; Binomial tress
69	Harrison and Sunar (2015)	OR	A. Uncertainty & Investment	✓				✓		Costly learning; Bayesian approach
72	Huang (2009)	EJOR	C. Production & Manufacturing		✓	✓	✓			Correlated demand forecasting
74	Inderfurth and Kelle (2011)	IJPE	D. Supply Chain & Logistics		✓		✓			Capacity; Procurement/purchasing practices; Long-term contracts
75	Julka et al. (2007)	IJPE	C. Production & Manufacturing		✓		✓	✓	✓	Manufacturing; Capacity expansion
77	Kamrad et al. (2005)	EJOR	B. R&D, Innovation & Technology	✓			✓			Innovation diffusion uncertainty
79	Keswani and Shackleton (2006)	EJOR	F. Valuation Models & Other			✓	✓			Project valuation with disinvestment
80	Kettunen et al. (2015)	EJOR	B. R&D, Innovation & Technology		✓		✓			Product development; Competition intensity; Innovation
82	Kim et al. (2008)	EJOR	A. Uncertainty & Investment		✓		✓			Investment time lags
85	Kort et al. (2010)	EJOR	A. Uncertainty & Investment		✓		✓			Flexibility; Lumpy vs. stepwise investment
86	Koussis et al. (2007)	ANOR	B. R&D, Innovation & Technology		✓		✓			R&D investments; Path dependency
93	Li and Wang (2010)	EJOR	C. Production & Manufacturing		✓		✓			Capacity planning; Switching operating option
95	Lin (2009a)	EJOR	C. Production & Manufacturing		✓		✓			Flexible production scale; Investment; Maximum NPV
96	Lin (2009b)	EJOR	C. Production & Manufacturing		✓		✓			Production policy; External financing
97	Liu and Wong (2011)	MS	B. R&D, Innovation & Technology		✓	✓	✓			Capital structure; Default; Intellectual capital; R&D and patent-based metrics

103	Messina and Bosetti (2006)	ANOR	E. Energy, Natural Resources & Environment		✓	✓	✓		Land conversion; Investment timing
107	Morellec et al. (2015)	MS	A. Uncertainty & Investment		✓	✓	✓		Investment; Capital structure; Credit supply; Competition
116	Osadchiy et al. (2015)	MS	D. Supply Chain & Logistics		✓	✓	✓		Supply chain network; Empirical study
117	Pendharkar (2010)	EJOR	B. R&D, Innovation & Technology			✓	✓		IT investment analysis
121	Qin and Nembhard (2010)	IJPE	C. Production & Manufacturing	✓			✓		Workforce agility as a production/operations input
122	Ramasesh et al. (2010)	IJPE	C. Production & Manufacturing		✓		✓		Process-switching; Product life cycle
123	Reindorp and Fu (2011)	EJOR	C. Production & Manufacturing		✓		✓		Equipment replacement; Maintanance
124	Reyck et al. (2008)	EJOR	F. Valuation Models & Other	✓		✓	✓		Investment; Sensitivity analysis
125	Richardson et al. (2013)	IJPE	C. Production & Manufacturing		✓		✓		Equipment replacement; Delivery lead times
126	Rombotis et al. (2012)	IJPE	C. Production & Manufacturing		✓		✓		Remanufacturing; Closed loop supply chains; Reverse logistics
127	Santiago and Vakili (2005)	MS	B. R&D, Innovation & Technology		✓		✓		R&D projects; Managerial flexibility
128	Sbuelz and Caliari (2012)	EJOR	A. Uncertainty & Investment		✓		✓		Corporate growth options
130	Secomandi (2010)	MS	C. Production & Manufacturing		✓		✓		Inventory policy; Production; Petroleum; Natural gas
131	Shibata (2008)	EJOR	A. Uncertainty & Investment		✓			✓	Incomplete information; Unobservable state variable
133	Shibata and Nishihara (2015)	EJOR	A. Uncertainty & Investment		✓		✓		Investment; Debt structure; Debt issuance limit constraints
135	Shin and Ariely (2004)	MS	F. Valuation Models & Other			✓		✓	Options; Aversion to loss
139	Szmerekovsky (2007)	EJOR	C. Production & Manufacturing		✓		✓		Production scheduling; Heuristics
140	Takezawa et al. (2007)	IJPE	D. Supply Chain & Logistics		✓		✓		Forward supply contract; Risk hedging; Ownership structure
141	Thijssen et al. (2004)	EJOR	A. Uncertainty & Investment		✓			✓	Investment; Bayesian updating
144	Van Mieghem (2007)	MS	C. Production & Manufacturing	✓			✓		Capacity; Inventory; Network design
146	Wallace (2010)	ANOR	F. Valuation Models & Other		✓		✓		Stochastic Programming; Relation to option theory
147	Wallace and Choi (2011)	IJPE	D. Supply Chain & Logistics		✓			✓	Supply chain management; Information Stages; Flexibility
148	Wang and Yang (2012)	IJPE	B. R&D, Innovation & Technology		✓	✓	✓		R&D management; New product development
151	Wang and Dyer (2012)	OR	F. Valuation Models & Other	✓			✓		Valuation; Investment; Copulas
155	Wu et al. (2009)	ANOR	B. R&D, Innovation & Technology		✓	✓	✓		Enterprise resources planning (ERP)
156	Wu et al. (2010)	IJPE	D. Supply Chain & Logistics		✓		✓		Supply chain contracts; Risk aversion
157	Xu et al. (2012)	IJPE	C. Production & Manufacturing		✓		✓		Modular production; Option to Modularization
158	Yan and Dooley (2010)	IJPE	D. Supply Chain & Logistics		✓		✓		Supply chain; Inventory replenishment; Electronic surplus market; Learning
159	Zambujal-Oliveira and Duque (2011)	EJOR	C. Production & Manufacturing		✓		✓		Asset replacement
160	Zapata and Reklaitis (2010)	EJOR	B. R&D, Innovation & Technology		✓		✓		Investment; MC Simulation

163	Ziedonis (2007)	MS	B. R&D, Innovation & Technology			✓	✓			Licensing; university-industry linkages; knowledge transfer
164	Zmeškal (2010)	EJOR	F. Valuation Models & Other	✓				✓		Fuzzy sets; binomial lattice

Panel A.2: Single-firm, Context-specific

Article	Citation	Journal	General Theme	Theory		Empirical	Information		Principal/	Authors'
No.	Authors (Year)	Acronym	Topic	New	Refine	or Applied	Complete	Incomplete	Agent	Keywords
6	Armony and Maglaras (2004a)	OR	D. Supply Chain & Logistics		✓		✓			Service networks; Multiclass queueing systems; Call-back option; Call centers
7	Armony and Maglaras (2004b)	OR	D. Supply Chain & Logistics		✓		✓			Service networks; Call centers; Nash equilibrium
12	Bastian-Pinto et al. (2010)	ANOR	E. Energy, Natural Resources & Environment		✓	✓	✓			Flex fuel car; Switching fuels
14	Benaroch et al. (2012)	EJOR	C. Production & Manufacturing		✓		✓			Services outsourcing; Backsourcing; Switching
19	Bøckman et al. (2008)	EJOR	E. Energy, Natural Resources & Environment			✓	✓			Investment; Energy; Hydropower
20	Boomsma et al. (2012)	EJOR	E. Energy, Natural Resources & Environment		✓	✓	✓			Investment; Renewable energy; Support schemes
24	Bulmuş et al. (2013)	IJPE	C. Production & Manufacturing		✓		✓			Inventory; Remanufacturing; Capacity; Product lifecycle
30	Chen et al. (2015)	EJOR	C. Production & Manufacturing		✓	✓	✓			Oil refinery operations; Procurement
33	Chou et al. (2007)	IJPE	C. Production & Manufacturing		✓	✓	✓			Capacity strategy planning; Semiconductor manufacturing
41	d'Halluin et al. (2007)	EJOR	B. R&D, Innovation & Technology		✓		✓			Telecommunications; Network capacity
42	Di Corato and Montinari (2014)	EJOR	E. Energy, Natural Resources & Environment		✓		✓			Switching option; Municipal waste; Recycling
44	Dimakopoulou et al. (2014)	IJPE	B. R&D, Innovation & Technology		✓	✓	✓			RFID technology; Case study
50	Farzan et al. (2015)	ANOR	E. Energy, Natural Resources & Environment		✓		✓			Investment; Valuation; Microgrids
51	Felix and Weber (2012)	EJOR	C. Production & Manufacturing			✓	✓			Investment; Storage; Recombining trees
53	Folta et al. (2010)	MS	F. Valuation Models & Other			✓		✓		Self-employment; Entrepreneurship; Learning
55	Franklin Jr. (2015)	ANOR	E. Energy, Natural Resources & Environment		✓		✓			Investment; Network element; Mobile telecommunication
70	Heikkinen and Pietola (2009)	EJOR	E. Energy, Natural Resources & Environment		✓	✓		✓		Investment; Agriculture; Time-correlated income
76	Kallio et al. (2012)	EJOR	E. Energy, Natural Resources & Environment		✓	✓		✓		Investment; Plantation forests
81	Khansa and Liginlal (2009)	EJOR	B. R&D, Innovation & Technology		✓			✓		Investment; Security process innovations; information security

89	Kunsch et al. (2008)	EJOR	E. Energy, Natural Resources & Environment		✓	✓	✓	Environment; Discount rate
90	Lai et al. (2010)	OR	C. Production & Manufacturing	✓			✓	Gas storage valuation
91	Lai et al. (2011)	OR	C. Production & Manufacturing		✓	✓	✓	Gas storage valuation
94	Li et al. (2015)	IJPE	E. Energy, Natural Resources & Environment		✓	✓	✓	Biofuel; Valuation; Case study
102	Marcus and Anderson (2006)	OR	D. Supply Chain & Logistics			✓	✓	Low-price guarantees; Inventory; Production; Transportation
108	Morgan and Ngwenyama (2015)	IJPE	B. R&D, Innovation & Technology		✓	✓	✓	IT investments; Software upgrades; Learning
109	Muñoz et al. (2011)	ANOR	E. Energy, Natural Resources & Environment		✓	✓	✓	Wind energy investments; MC simulation; Case studies
111	Nadarajah et al. (2015)	MS	C. Production & Manufacturing	✓		✓	✓	Gas storage valuation; Linear Programs
112	Nigro et al. (2014)	IJPE	B. R&D, Innovation & Technology		✓		✓	R&D portfolio selection; Biopharmaceuticals; Open innovation
118	Pennings and Sereno (2011)	EJOR	B. R&D, Innovation & Technology		✓	✓	✓	Compound option; Jump-diffusion process; R&D Pharmaceutical industry
119	Petrasek et al. (2015)	ANOR	E. Energy, Natural Resources & Environment		✓	✓	✓	Bear land value; Forestry; Product life cycle
142	Thompson et al. (2004)	OR	E. Energy, Natural Resources & Environment			✓	✓	Energy; Deregulated electricity markets
143	Tseng and Lin (2007)	OR	E. Energy, Natural Resources & Environment		✓	✓	✓	Power plant valuation; Natural resources
145	Wahab and Lee (2011)	ANOR	F. Valuation Models & Other	✓			✓	Swing options; Energy; Regime-switching process; Lattices
153	Wong et al. (2011)	IJPE	C. Production & Manufacturing		✓	✓	✓	Supply chain; Postponement option

Panel B.1: Multi-firm/Games, General context

Article No.	Citation Authors (Year)	Journal Acronym	General Theme Topic	Theory New	Theory Refine	Empirical or Applied	Information Complete	Information Incomplete	Principal/ Agent	Authors' Keywords
4	Antelo and Bru (2010)	IJPE	C. Production & Manufacturing		✓			✓		Restructuring in-house production; Outsourcing; Asymmetric information
8	Azevedo and Paxson (2014)	EJOR	A. Uncertainty & Investment		✓		✓	✓	✓	Review paper; Real options games
10	Ball et al. (2015)	EJOR	C. Production & Manufacturing		✓	✓			✓	Multi-agent decision-making
11	Banerjee et al. (2014)	EJOR	A. Uncertainty & Investment		✓		✓			Investment; Nash bargaining solution; Agency problem
17	Bhattacharya et al. (2015)	MS	B. R&D, Innovation & Technology		✓				✓	R&D partnerships; Options contracts; Agency problem
25	Burnetas and Ritchken (2005)	MS	D. Supply Chain & Logistics		✓		✓			Supply chain contracts;Options;

26	Cassiman and Ueda (2006)	MS	B. R&D, Innovation & Technology		✓		✓			Innovation; R&D; Start-ups
29	Chen (2012)	IJPE	D. Supply Chain & Logistics		✓	✓	✓			Two-echelon supply chain; Cooperative timing of investment
31	Chevalier-Roignant et al. (2011)	EJOR	A. Uncertainty & Investment		✓		✓	✓	✓	Strategic investment
35	Chronopoulos et al. (2014)	EJOR	A. Uncertainty & Investment		✓		✓			Investment; Duopoly; Competition; Risk aversion
36	Clark and Konrad (2008)	MS	B. R&D, Innovation & Technology		✓		✓			R&D; Fragmented property rights; Patent
57	Gaur et al. (2011)	MS	A. Uncertainty & Investment	✓			✓			Incomplete markets; Securitisation; Financial innovation
63	Gu and Zhang (2012)	IJPE	D. Supply Chain & Logistics		✓		✓			Supply chain; Endogenous default risk
65	Haanappel and Smit (2007)	ANOR	A. Uncertainty & Investment		✓		✓			Asset returns; Growth options
71	Hsu and Lambrecht (2007)	ANOR	B. R&D, Innovation & Technology		✓			✓		Option game; Preemption; Asymmetric information
73	Huisman and Kort (2004)	EJOR	B. R&D, Innovation & Technology		✓		✓			Technological uncertainty; Preemption
78	Kamrad and Siddique (2004)	MS	D. Supply Chain & Logistics		✓		✓			Supply contracts; reaction options
84	Kong and Kwok (2007)	EJOR	A. Uncertainty & Investment		✓		✓			Options game; Preemption
87	Kulatilaka and Lin (2006)	MS	B. R&D, Innovation & Technology		✓		✓			Licensing; Innovations
88	Kumar and Turnbull (2008)	MS	B. R&D, Innovation & Technology		✓		✓			Licensing; Financial innovations
92	Leung and Kwok (2012)	EJOR	B. R&D, Innovation & Technology		✓			✓		Patents; Information asymmetry
98	Liu and Nagurney (2013)	ANOR	D. Supply Chain & Logistics	✓			✓			Supply chain, Outsourcing as an option; Equilibrium
99	Löffler et al. (2012)	EJOR	D. Supply Chain & Logistics		✓			✓		Supplier switching; Supply chain contracts; Information asymmetry
101	Lukas and Welling (2014)	EJOR	E. Energy, Natural Resources & Environment		✓		✓			Supply chain management; Eco-efficiency
104	Mittendorf (2004)	MS	A. Uncertainty & Investment		✓			✓	✓	Incentives; Information revelation
105	Moon et al. (2011a)	IJPE	C. Production & Manufacturing		✓		✓			Outsourcing vs. Joint venture;
106	Moon et al. (2011b)	IJPE	D. Supply Chain & Logistics		✓		✓			Supply contracts; billateral negotion
110	Murto et al. (2004)	EJOR	A. Uncertainty & Investment		✓		✓			Real options game
113	Nishihara and Fukushima (2008)	EJOR	A. Uncertainty & Investment		✓			✓		Real options game; Incomplete information
114	Oh and Özer (2013)	MS	D. Supply Chain & Logistics	✓				✓		Capacity planning; Information sharing
115	Ohyama and Tsujimura (2008)	EJOR	E. Energy, Natural Resources & Environment		✓		✓			Environmental policy; Innovation; Optimal timing
120	Pfeiffer and Schneider (2007)	MS	B. R&D, Innovation & Technology		✓				✓	Sequential capital budgeting; Residual income; Accounting adjustments
132	Shibata and Nishihara (2011)	EJOR	A. Uncertainty & Investment		✓			✓	✓	Privatisation; Incomplete information; Agency

136	Siddiqui and Takashima (2012)	EJOR	E. Energy, Natural Resources & Environment	✓	✓	Switching option; Capacity; Infrastructure investments
137	Skintzi et al. (2008)	IJPE	C. Production & Manufacturing	✓	✓	Supply chain; Outsource vs acquire specialised subsidiary
138	Spinler and Huchzermeier (2006)	EJOR	C. Production & Manufacturing	✓	✓	Capacity options; Dated services and non-storable goods; Risk sharing
149	Wang et al. (2012)	IJPE	D. Supply Chain & Logistics	✓	✓	Supply contracts; Quantity flexibility
150	Wang and Tsao (2006)	IJPE	D. Supply Chain & Logistics	✓	✓	Supply contracts; Bidirectional options (increase or decrease order size)
152	Wang et al. (2015)	IJPE	D. Supply Chain & Logistics	✓	✓	Timing trades along a supply chain; Mergers of suppliers or manufacturers
154	Wu and Kleindorfer (2005)	MS	D. Supply Chain & Logistics	✓	✓	Capacity options; B2B exchanges; Supply chain management
161	Zhao et al. (2013)	IJPE	D. Supply Chain & Logistics	✓	✓	Supply chain options; Spot markets
162	Zheng and Negenborn (2015)	IJPE	D. Supply Chain & Logistics	✓	✓	Supply chain management; Generalized Nash Bargaining model

Panel B.2: Multi-firm/Games, Context-specific

Article	Citation	Journal	General Theme	Theory		Empirical	Information		Principal/	Authors'
No.	Authors (Year)	Acronym	Topic	New	Refine	or Applied	Complete	Incomplete	Agent	Keywords
2	Al sharif and Qin (2015)	ANOR	D. Supply Chain & Logistics		✓	✓	✓			Procurement/lease contracts; Price flexibility; Time charter contracts
9	Baecker et al. (2010)	ANOR	E. Energy, Natural Resources & Environment		✓		✓			Option game; Telecommunications; Regulation via price barriers
38	Cui et al. (2014)	MS	D. Supply Chain & Logistics		✓		✓			Ticket resale options; Event tickets
49	Dulluri and Srinivasa Raghavan (2008)	EJOR	D. Supply Chain & Logistics		✓	✓	✓			Collaboration options
59	Glasserman and Wang (2011)	MS	G. Other Topics	✓		✓	✓			Application; CAP program in U.S. banking
60	Graf and Kimms (2011)	EJOR	D. Supply Chain & Logistics	✓			✓			Capacity control; Airline strategic alliances
61	Graf and Kimms (2013)	IJPE	D. Supply Chain & Logistics	✓			✓			Capacity control; Airline strategic alliances
83	Ko et al. (2011)	IJPE	A. Uncertainty & Investment		✓		✓			Venture capital; Option game; Duopoly;
100	Lukas et al. (2012)	EJOR	A. Uncertainty & Investment		✓		✓			Mergers and acquisitions; Contingent earnouts
129	Scandizzo and Ventura (2010)	EJOR	E. Energy, Natural Resources & Environment		✓	✓	✓			Transport; Concession contract; Nash equilibrium
134	Shibata and Yamazaki (2010)	EJOR	E. Energy, Natural Resources & Environment		✓		✓			Regulation; Competition; Real options game